Ice Nuclei Inventory: Wasatch Weather Modification Experimental Area

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ICE NUCLEI INVENTORY:

WASATCH WEATHER MODIFICATION EXPERIMENTAL AREA

by

William F. Slusser

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Soil Science and Biometeorology

ACKNOWLEDGMENTS

This study was carried out as part of the Wasatch Weather Modification Project, funded by the Office of Atmospheric Water Resources, U.S. Bureau of Reclamation, under contract No. 14-06-0-6820 with Utah State University. The National Center for Atmospheric Research (NCAR), which is sponsored by the National Science Foundation, assisted by loaning equipment through its Field Observing Facility. In addition, the counsel of Mr. Gerhard Langer of NCAR was vital to getting the study underway.

I wish to express my thanks to Mr. William McNeil who provided the rawindsonde data and notified me of the start of experimental events at all hours of the day (and night). The counsel of Drs. Ashcroft, Chappell, and Reynolds, and other members of the advisory committee, was greatly appreciated. And Dee, thanks.

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ABSTRACT

ICE NUCLEI INVENTORY:

WASATCH WEATHER MODIFICATION EXPERIMENTAL AREA

by

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Utah State University, 1973

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Several large sources of ice nuclei were identified for the Wasatch Weather Modification Experimental Area. When stable air masses remained over the area for several days, ice nuclei concentrations as large as 1750 per liter (measured at -20 C) were found at the surface. Concentrations as large as 6000 per liter were measured with an airborne ice nuclei counter over the smelter industry of the Salt Lake Valley. Ice nuclei concentrations during storm periods were usually less than 3 per liter, indicating an excellent potential for increasing precipitation amounts over the Wasatch Mountains through the release of artificial ice nuclei.

Ice nuclei measurements taken during and following seeding activities indicate that nuclei are not being trapped in the Cache Valley and are not being funnelled into areas upwind of the seeding generators. The measure-

ments also indicated that nuclei are getting into the seeding area, at least at the ground level. Residual ice nuclei were found in the experimental area--an average of 7.5 hours for ground seeders and 4.6 hours for airborne seeders--following seeding activities.

Stability, wind direction, and cloud top temperatures were found to be the meteorological conditions most closely related to ice nuclei concentrations although this could not be shown through the use of statistical tests.

(129 pages)

INTRODUCTION

Background

Since ancient times man has dreamed of manipulating the weather, but it has only been recently that he has developed the techniques by which his dreams may be realized. Since the discovery, in 1946, that dry ice and silver iodide were effective ice nuclei [Schaefer, 1968a] many weather modification projects were undertaken to increase the precipitation amounts in some of the drier areas of this country. Attempts to increase precipitation were not always successful, and in some instances a decrease in precipitation was observed [Tilson, 1969]. Schaefer [1967] suggested that decreases may be due to an over abundance of ice nuclei. Other projects may have been unsuccessful because they could not get the nuclei into the clouds, or did not know where the nuclei went when released.

Thus, it was found that precipitation could be increased or decreased by introducing ice nuclei into supercooled clouds. And, it is apparent that there is a great need for ice nuclei inventories and budgets. Without these it is not possible to predict the effects of the addition of further ice nuclei by seeding operations. Studies are also needed to determine where seeding material goes when released.

Many basic questions must be answered to assure the success of any weather modification project. This thesis is concerned with two of these questions: first, do the natural background ice nuclei numbers in the experimental area need supplementation; second, is effluent released during seeding operations getting into the clouds over the target areas.

Study area

This investigation was conducted as a support activity for the Wasatch Weather Modification Project. The main purpose of the Project was to study the feasibility of increasing precipitation through the release of artificial ice nuclei. The major portion of the Wasatch Weather Modification Experimental Area is shown in Figure 1. For the present study, ice nuclei measurements were taken in all parts of the area accessible by road. During the first year counting operations were concentrated in the Cache Valley which lies within the target area directly downwind of the ground based ice nuclei generators. Large numbers of measurements were also taken in the Salt Lake Valley which was shown to be a major source of artificial ice nuclei.

The Cache Valley extends northward from northeastern Utah into southeastern Idaho. It is oriented in a north-south direction and bordered on the west and east by two abrupt mountain ranges, each rising to as much as 5000 feet above the Valley floor [see Figure 1]. The Valley

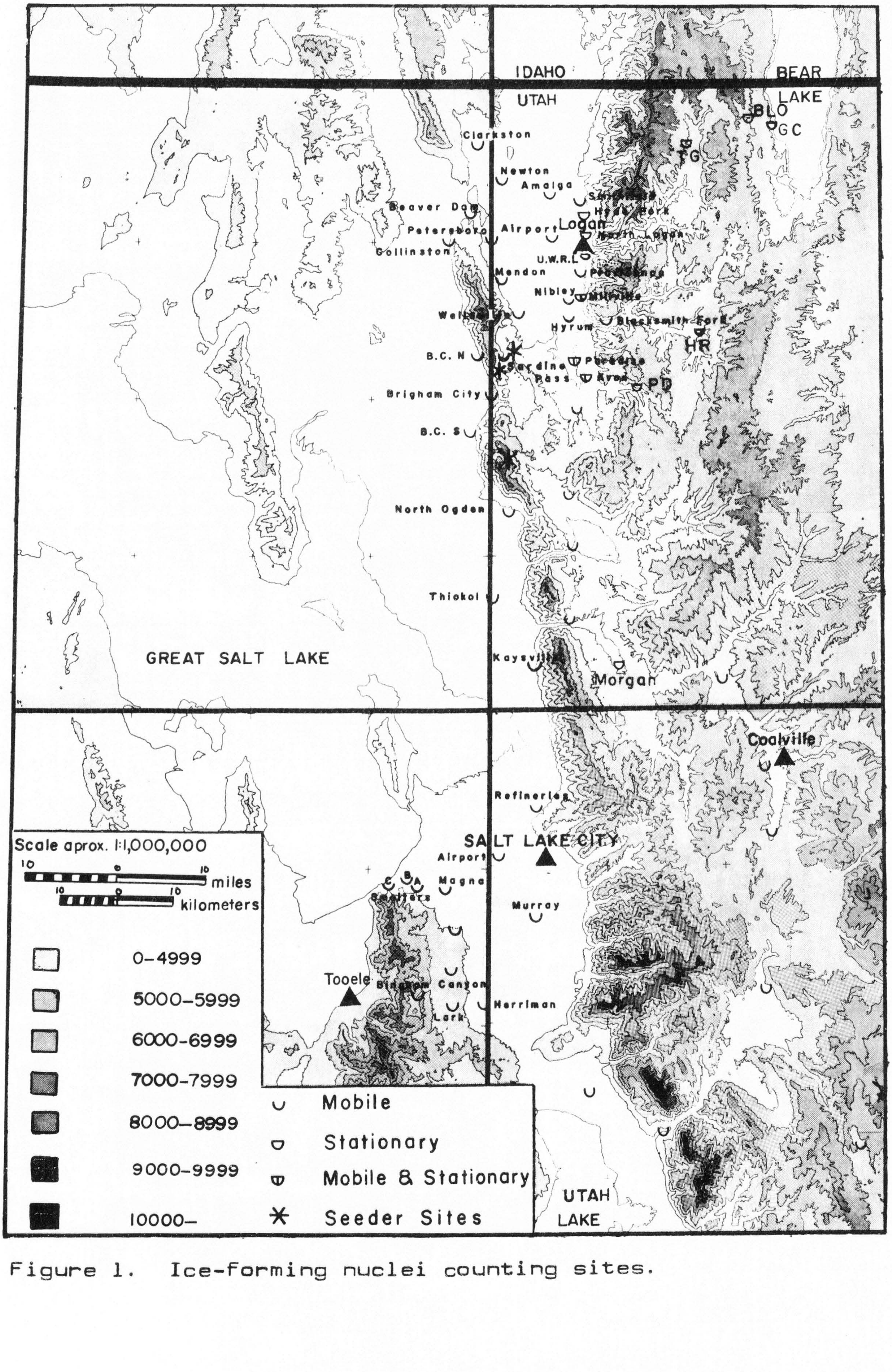


Figure 1. Ice-forming nuclei counting sites.

averages somewhat under 10 miles wide and is about 60-70 miles long. Within the Valley there is a gentle slope downward to the Bear River which empties out of the Valley through a short, narrow canyon. Except for this outlet the terrain goes upward in all directions from the Valley floor. The dominant westerly component of the synoptic winds, the abrupt, relative heights and north-south orientation of the ranges on each side, and the quasi-U-shaped characteristics of the Valley floor combine to provide a high trapping potential for surface released contaminants (Reynolds, 1967).

The area under investigation was the Utah portion of Cache Valley. The total population of this portion is approximately 30,000 including the Utah State University students. The southern end of the Valley is the most populated with Logan (Utah), a university town, being the largest community. Logan serves as a central place for the smaller towns and villages throughout the Valley. Utah State University is the primary employer and the only organization in the Valley which employs more than 100 people on a year round basis.

Another large section of the economy includes agricultural processing. The meat packers, cheese factories, seasonally operated sugar and canning factories each contribute to the pollution problem. The heating plants of the University and the LDS Temple also contribute as do the local dumps of each city and village where trash is burned, mostly on weekends. The only sawmill in the Valley is not permitted to burn any of its waste. [A new manufacturing plant which burns most of its wood scrap was not in operation during the experimental period.]

The main highway through the Valley branches at Logan. The highway along the east side of the Valley brings commuters and shoppers to and from the Logan area. The southwest branch connects Logan with the Wasatch front and Salt Lake City. This highway also sustains heavy commuter traffic as well as service traffic and seasonal recreation traffic between Salt Lake City, Logan, and Bear Lake. The travel in winter from Logan to Bear Lake is more moderate, but varies considerably with seasonal variations in skiing, hunting, fishing, and snowmobiling.

Salt Lake City is near the eastern edge of a great valley which includes the Great Salt Lake. This valley is occasionally interrupted by somewhat scattered mountains. The eastern border of the Salt Lake Valley is the north-northwest/south-southeast oriented Wasatch Front which rises abruptly from 3000 to 5000 feet above the Valley floor.

The concentration of human population and other air pollution sources lies in a narrow strip just to the west of the Wasatch Front, beginning to the south of Provo and extending northward to a little north of Brigham City.

Salt Lake City and environs, and Ogden and environs, all have enough industries, people, and traffic to justify concern over the possibility of local sources of high ice nuclei concentrations.

Ice nuclei and nucleation

It is generally recognized that the coexistence of the ice phase and the supercooled liquid phase of water in a cloud is one of the conditions that can lead to precipitation release in the atmosphere. This is the basis of the well known Bergeron-Findeisen or ice crystal mechanism of precipitation formation. The study of the initiation and development of the ice phase is then of fundamental importance in understanding one of the known important processes which often results in precipitation.

Nucleation is the process by which the ice crystal is initiated at certain loci. Nucleation which occurs without the intervention of a foreign substance is known as homogeneous or spontaneous nucleation. Nucleation which occurs through the intervention of, or upon a suitable foreign substance, or a surface of the same substance in a different state, is called heterogeneous nucleation. In ice nucleation, without regard to the manner of transition, the nuclei are correctly referred to as ice or ice-forming nuclei. But the term freezing nuclei has been frequently used rather loosely with the same meaning.

Although heterogeneous nucleation is more common in nature, according to Fletcher (1969), homogeneous nucleation does occur in the temperature range -33 C to -41 C depending upon the droplet size. The larger the droplet, the higher the temperature at which nucleation occurs. Heterogeneous nucleation can occur at much higher temperatures. The temperature at which a given substance initiates the growth of an ice crystal depends on such things as crystal structure, solubility, wettability, imperfections in the surface structure, purity, stability, and conditioning. The results of many experimenters indicate that there is a steady exponential increase in the number of active ice nuclei with decreasing temperature.

Ice nuclei can initiate the formation of ice crystals in several different ways: the nuclei can act as a surface for direct sublimation of the vapor (deposition nucleus); condensation can occur on the surface of the nuclei followed by freezing (freezing nucleus); the ice nuclei can enter the supercooled droplet directly at the surface or in some cases the nuclei can be present in the droplet during supercooling (immersion nucleus). Contact nucleation occurs when a particle collides with a water drop and nucleates it.

Since nucleation does not always require the presence of ice nuclei or of a foreign substance, the counting of ice nuclei may not give a good indication of the number of ice crystals present. This is an important point since it is the number of ice crystals present which is vital to precipitation formation and not directly the number of ice nuclei present. A review of the literature by Chappell (1970) indicated little agreement between ratios of ice crystal concentration to ice nuclei concentration found by different experimenters. There was an indication that the ratio may be temperature dependent with ratios larger than 1000:1 for temperatures above -10 C and ratios as small as 1:1 for temperatures below -15 C. The larger ratios may have been due in part to the inability of counters to measure ice nuclei active at temperatures above -15 C. The findings of Grant (1968) indicate that there is close to a 1:1 relationship between ice nuclei and ice crystal numbers during many of the storms which occur in the Climax, Colorado area.

Background ice nuclei

The number of ice crystals needed to optimize precipitation amounts varies according to the particular temperature, moisture, and other meteorological conditions associated with a cloud or cloud system (Grant, Chappell, and Mielke, 1968). If seeding is performed when sufficient ice crystals are already present, a decrease in precipitation may result. There are many possible sources of nuclei which may cause high ice nuclei numbers. Rosinski (1970) noticed sharp increases in nuclei counts with increases in wind speeds and attributed these counts to soil particles convected into the air stream by the wind. Decreases in precipitation over large cities thought to be due to inadvertent cloud seeding by air pollution has been reported by Feig [1968]. Large concentrations of ice nuclei due to pollution have also been reported over and downwind of large cities by Telford [1960], Schaefer [1967], Mohnen and Vonnegut [1968], Langer [1968], and Hobbs and Locatelli [1970]. These indicate that where concentrations of nuclei have not become excessive, increases in precipitation amounts are found both over the city and downwind of the city. But where ice nuclei concentrations are above the optimum level for a given set of meteorological conditions, increases were found only in areas downwind of the city where the large concentrations have become diluted. Frederick [1970] found that cool season precipitation in urban areas of the eastern United States is not randomly distributed through the week, and attributed this to pollution produced by man's activities.

Hogan [1967], Morgan and Allee [1968], Schaefer [1966] and others have pointed out that the reaction of iodine with the lead in automobile exhaust can produce large numbers of ice nuclei. Langer [1969a] pointed out that iodine is not necessary to activate the lead in automobile exhaust. Photochemical generation of lead oxide is, therefore, probably an important source of ice nuclei in areas of heavy automobile usage. Schaefer [1968b] mentions that wood burning may constitute a ready source of material for combination with auto exhausts in the production of ice nuclei.

In a study of ice nuclei measurements in Canada, Crozier [1969a] found that high counts were more frequent in the afternoon than in the morning. He found that ice nuclei concentrations would increase with a decrease in lapse rate. The counts were lowest during inversions and became lower as the inversion became closer to the surface. He thought this to be due to the concentration of nuclei in a layer at the top of the inversion with little or no mixing taking place.

Prabhakar and Murty [1962] reported that ice nuclei concentrations rise initially with the onset of showery rain and decrease following prolonged rain. Bigg and Meade [1959] have also reported this occurrence. Hobbs and Locatelli [1970] found, in the Pacific Northwest, that this only occurs when fairly strong mixing was taking place between cloud base and ground.

Generator released effluent

In past weather modification projects it was found that effluent released from ground based generators was sometimes not reaching target areas [Warburton and Young, 1968]. On many occasions effluent descended and was trapped in valleys, or it funnelled through these valleys into what were supposed to be control areas upwind of the generator site [Shumway, 1966; Langer et al, 1967; U.S. Bureau of Reclamation, 1968].

Statement of Problem

Although, as suggested in the previous section, there is reason to believe that under certain meteorological conditions the numbers of ice nuclei may often be sufficient to make seeding unnecessary, actual measurements are not available for most areas of the United States. Even in areas where the government is sponsoring large weather modification projects, little information is available on the average background ice nuclei counts, and there is essentially no information on how the numbers of ice nuclei vary spatially, temporally, and under different meteorological conditions.

Cloud seeding to increase precipitation amounts is based on the assumption that there is a deficit of naturally occurring ice crystals. If this is not the case, however, overseeding may occur with a resultant decrease in precipitation. This usually results from an over competition for available moisture with the result that crystals cannot grow large enough to fall. It is obvious that there is need for determining the ice nuclei concentrations in an area during both seeded and nonseeded periods.

The purpose of this study is to investigate the ice nuclei concentration in the Wasatch Weather Modification Experimental Area with the following objectives in mind:

1. To determine background nuclei concentrations along with their spatial and temporal variations.

2. Ice nuclei concentrations were also studied during seeding activities in order to:

   a) determine whether ice nuclei are descending into the Valley;

   b) determine whether ice nuclei are being trapped or pooled in the Valley;

   c) determine the time period that ice nuclei remain trapped in the Valley after seeding has been discontinued (provided they are found to be trapped as in 2b above);

   d) determine whether seeding material is being channeled upwind of the seeder through canyons;

   and,

   e) determine if nuclei are reaching target areas.

3. To determine relationships between nuclei concentrations and various meteorological conditions.

PROCEDURES

Collection of Data

Procedures varied from year to year in order to answer the questions posed in the objectives and to utilize the available equipment to the maximum in data collection. During the first year, two ice nuclei counters were available.

Data were collected through the use of NCAR Accoustical Ice Nuclei Counters on loan from the National Center for Atmospheric Research (NCAR). The characteristics of the Counter will be briefly discussed here, and are more fully described by Langer et al (1967), NCAR (1967), Steele et al, (1967), Auer and Veal (1968), and Langer (1969b).

Air from a height of 2 meters above the ground is drawn through the counter at a rate of 10 liters per minute. Incoming air first passes through a humidifier where it is exposed to a warm water surface which warms and humidifies the air. At the same time, large dust particles which may activate the sensor are removed by the humidifier. The water temperature is kept at 25 C. Air leaves the humidifier at about 90 percent saturation. While entering the humidifier, the air receives condensation nuclei from a sodium chloride aerosol generator which contains a solution of $<.01$ percent NaCl. The object of this procedure is to produce a uniform and fairly dense cloud as the air flows into the mixing-type cold chamber, so that crystals forming on ice nuclei can grow to a size large enough to be counted (greater than 20μ). Although the chamber temperature can be varied, for this project the chamber was operated at -20 C. In the cold chamber, ice crystals grow about the ice nuclei for less than one minute before they are drawn through an accoustical counter and recorded.

The walls of the chamber are lined with a polyurethane foam along which glycol is wicked. This prevents frost forming on these walls which could then splinter off and grow large enough to be counted. Supersaturation within the chamber is about 0.5 percent.

Counting of ice nuclei in the atmosphere is not yet a precise science. There is not yet universal agreement as to which is the best procedure; the differences in results are sometimes substantial, and these differences vary a great deal (Langer, 1969b). There is some doubt as to whether or not the processes in the various cloud chambers actually represent natural atmospheric ice crystal formation processes. The existing instrumentation, including the NCAR counter, appear to be quite adequate for recognizing relative amounts of ice nuclei in the atmosphere, however, provided a single type of measurement system is used throughout the study.

Location of the ice nuclei counter

During the first year, counts were made primarily in and around Cache Valley with both stationary and quasi-mobile modes. In the stationary mode, consecutive 10 minute averages were made at a selected location for several hours. The location from which the stationary counter was operated for a given storm period was based on a Salt Lake City Weather Bureau forecast of wind direction. The specific site for the stationary counter during the first year was determined by the availability of a conventional 110 to 120 volt power source. A portable power plant was used with the counter during the second and third years; thus, the system was mobile.

There are several reasons why the stationary counter alone may not provide satisfactory data. First, wind directions at Salt Lake City may not be the same as those at the seeder site. Second, the location of this counter was determined by the wind direction at the beginning of a seeded period so the counter was not always in the best location during the latter stages of a storm. Third, studies by Henderson [1968] and Willis [1968] show that plume characteristics are unpredictable even when a given meteorological condition appears similar to a previous experience. For these reasons, counts were also made in a quasi-mobile mode. With this unit, five 2 minute averages were obtained at each of several locations.

During the second and third years, counts were made primarily at locations near the center and eastern border of the target area: Hardware Ranch, Tony Grove Ranger Station, and Bear Lake Overlook. Mobile operations at higher elevations within the target areas were not feasible due to the lack of roads and the great distances between suitable counting locations. Counts were also made at a single location during a given operation. As during the first year, this location was determined by predicted wind direction. With this counter, simultaneous 2 minute average counts were taken for periods of 8 hours or longer. Table 1 contains a list of the stations used with their elevations.

Ice nuclei concentrations were also measured in several other areas which could contribute nuclei to the experimental area. These areas included Ogden, Salt Lake City, Provo, and Heber. Counts were taken in areas as far away as Roosevelt, Utah. Most locations where ice nuclei concentrations were measured are shown in Figure 1.

A dense network of counting locations was set up in the Salt Lake Valley, as shown in Figure 2. This was the area in which ice nuclei concentrations were found to be consistently higher than in other areas where counts were taken. Airborne measurements were also taken simultaneously over this area by Atmospherics, Incorporated.

Table 1. Ice Nuclei Sampling Locations and Seeder Sites

Mode	Location (Symbol)	Elevation (Feet)
MOBILE	Cache Valley and Vicinity (CV)	
	Clarkston	4820
	Newton	4530
	Amalga	4440
	Smithfield	4580
	Beaver Dam	4850
	Petersboro	4600
	Logan Airport	4454
	Collinston	4600
	Providence	4540
	Mendon	4560
	Nibley	4520
	Millville	4639
	Wellsville	4585
	Blacksmith Fork	4996
	Hyrum	4789
	Sardine Pass	5820
	Paradise	4963
	Avon	5020
	Brigham City North	4335
	Brigham City	4590
	Brigham City South	4400
STATIONARY	Bear Lake Overlook (BLO)	7600
	Tony Grove Ranger Station (TG)	6800
	Garden City (GC)	5995
	Porcupine Dam (PD)	5650
	Hardware Ranch (HR)	5580
	Cache Valley	
	Hyde Park (HP)	4610
	North Logan (NL)	4785
	Utah Water Research Lab (UWRL)	4670
	Millville (M)	4639
	Paradise (P)	4880
	Avon (A)	4940
SEEDER SITES		
	Brigham City East (BCE)	7100
	Blue Hill (BH)	6127
	Willard Mountain (WM)	9116

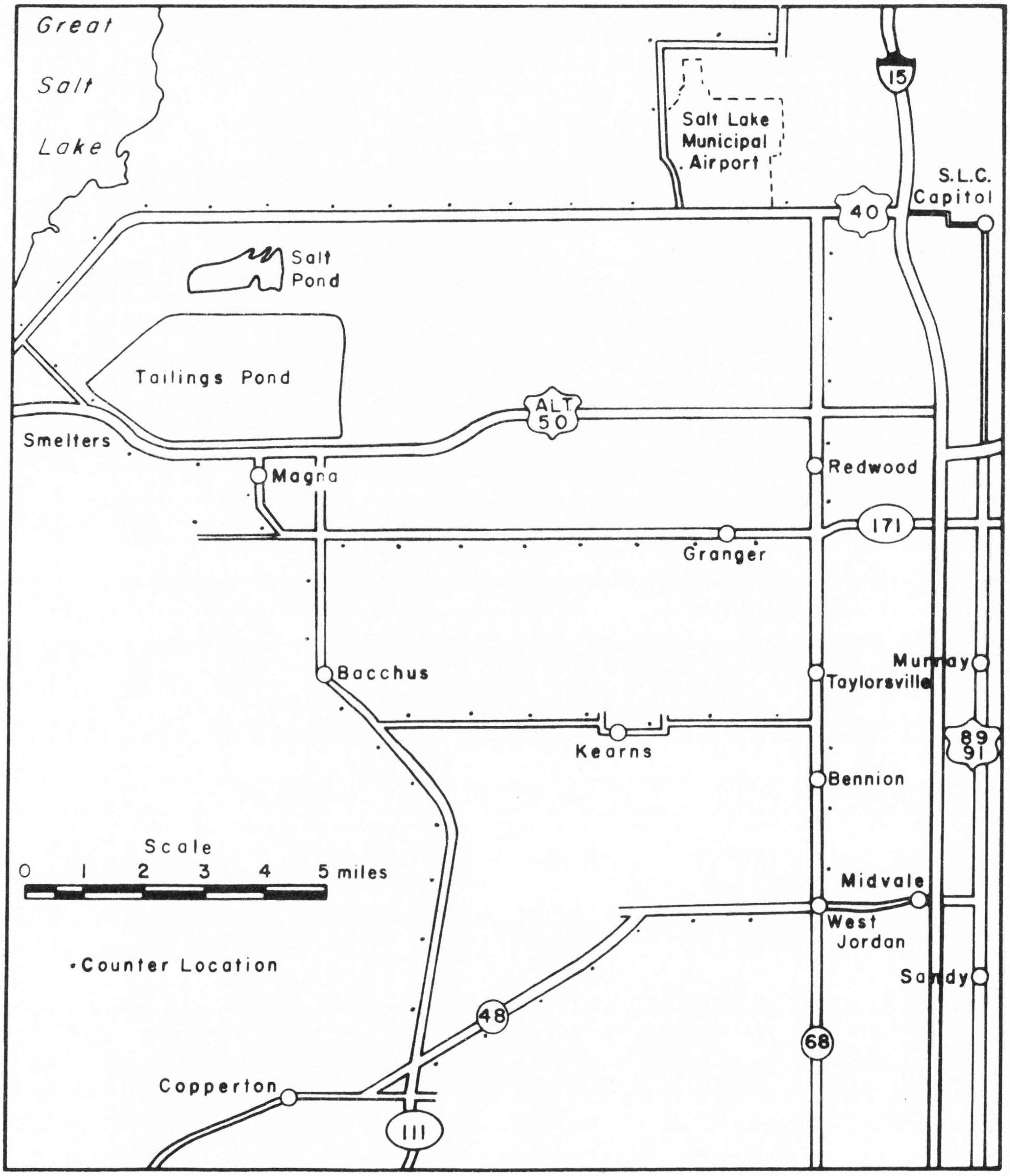


Figure 2. Ice nuclei counting sites--Salt Lake City study area.

Since the network or grid pattern consisted of 60 counting locations, a minimum of 12 hours would be required to complete a single run if five 2 minute average counts were taken, as was done during the rest of the mobile operations. Consequently, the median of three 2 minute average counts was used in the analysis. This allowed a run to be made in as little as 8 hours. To conserve even more time, counts were sometimes taken at every other location in areas where counts were consistently low on a given day.

To truly show spatial variations, concentrations should be measured simultaneously at all locations. With the equipment available this was impossible. Also, since as many as 10 hours were required to complete a single run, it was felt that temporal changes in ice nuclei concentrations would conceal any spatial variation which might exist. Therefore, the starting point and starting time varied from one experiment to the next. This was not intended to eliminate the effect of time, but to help show the effect of time, if one existed. Counts were also taken in a figure eight pattern to control the time factor.

A similar grid pattern was set up in the Cache Valley. Here, however, the variation in ice nuclei concentrations was greater at a given station than between stations. Thus, drawing meaningful isolines was impossible. The Valley experiment was discontinued after a few runs as it was very time consuming and the results were of questionable validity due to the temporal variations in ice nuclei concentrations.

Mounting the ice nuclei counter

During the first year the stationary counter was mounted in the back of a carry-all type vehicle. For this operation the vehicle was adequate, but its harsh ride made the carry-all less than ideal for mobile operations. For the mobile operation a second and smaller counter was mounted in the rear compartment of a Lark Cruiser. After removal of the rear seat cushion, its flat floor and large area provided easy accomodation for the counter. A small gasoline powered 1100 watt generator was used with this unit. While the power output was marginal for starting the counter, its size was ideal, since the generator had to be unloaded and loaded at each counting location. During operation, the generator was placed about 50 feet downwind of the air intake of the counter to avoid any possible contamination, although such contamination was not probable [Langer, 1968]. This unit was available for the first year only. During the remaining two years, the counter used the first year in the stationary mode was mounted in the back of a Dodge stationwagon. Its soft ride was better suited for transporting the counter long distances. To accomodate the counter the rear roof section of the wagon was raised 20 inches. A small electric generator was used to supply power.

Experimental Events

During the first year of operation only ground seeding was attempted, and the length of the seeded periods varied. The seeders were located to the west of Cache Valley near the mountain tops, as shown in Figure 3 (elevations of seeder sites are listed in Table 1).

During the second and third years, both ground and air seeding was used, and an 8 hour experimental period was employed. This operational event was divided into two 4 hour periods: a seeded and a nonseeded period. The period which was to be seeded was determined randomly. Actually, seeding was done only during the first 2 hours of the seeded period. The remaining 2 hours were to act as a buffer period to allow the effluent time to evacuate the area so that the nonseeded period would not be contaminated if it followed the seeded period.

Reduction of Data

The majority of the measurements were recorded by means of Rustrak recorders. Two minute average counts were interpreted from the Rustrak tapes and corrected for machine bias and elevation in accordance with Langer (1969b). These values were then recorded on punch cards. Ten minute, hourly, and 4 hourly averages were also calculated for

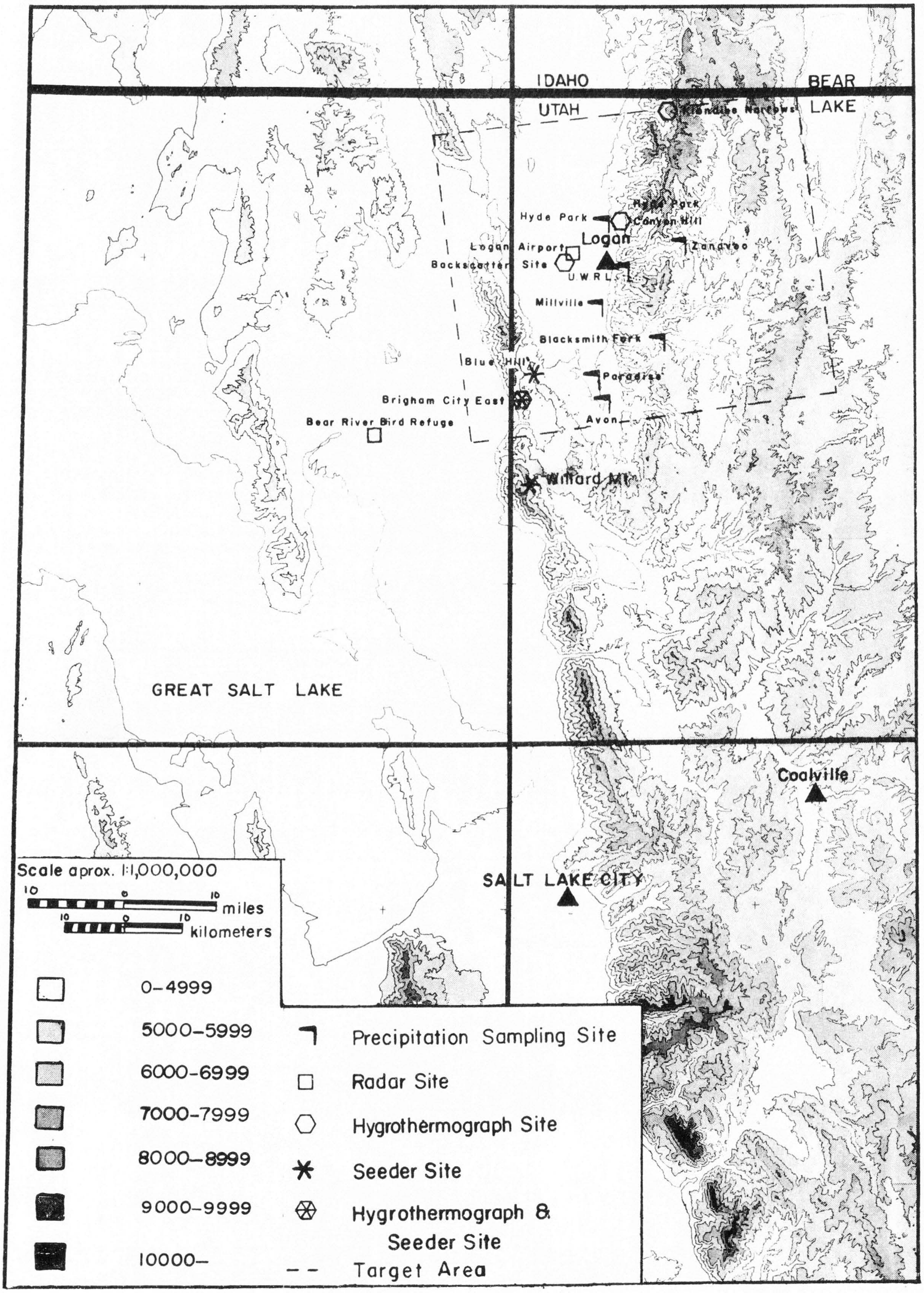


Figure 3. Equipment locations.

seeded and nonseeded periods of operational events. Four hour averages using lags of 1 and 2 hours were calculated to take into account the time required for effluent to reach the area in which measurements were taken. Ratios of seeded to nonseeded periods were then calculated using lag periods of 0, 1, and 2 hours.

During the first year, surface charts for days on which ice nuclei measurements were taken and the 3 previous days, along with vertical time cross sections of winds for the period beginning 3 days before and ending the day following ice nuclei counting operations, were prepared (see Figure 4). Pseudo-adiabatic diagrams giving vertical profiles for dew point, temperature, and wind were also prepared for the day of counting (Figure 5). All charts were prepared from Salt Lake City rawinsondes. The Salt Lake soundings were taken approximately 80 miles to the south of where ice nuclei were measured.

During the second and third years rawinsondes from both Salt Lake City and the Cache Valley were available. Data were used in analysis, but they were not worked up (or replotted) as the first year's data were because this process was time consuming and seemed to contribute little in facilitating the analysis.

Ice nuclei concentrations and other variables with similarly skewed distributions, such as rainfall, are hard to characterize climatically due to their extreme variability.

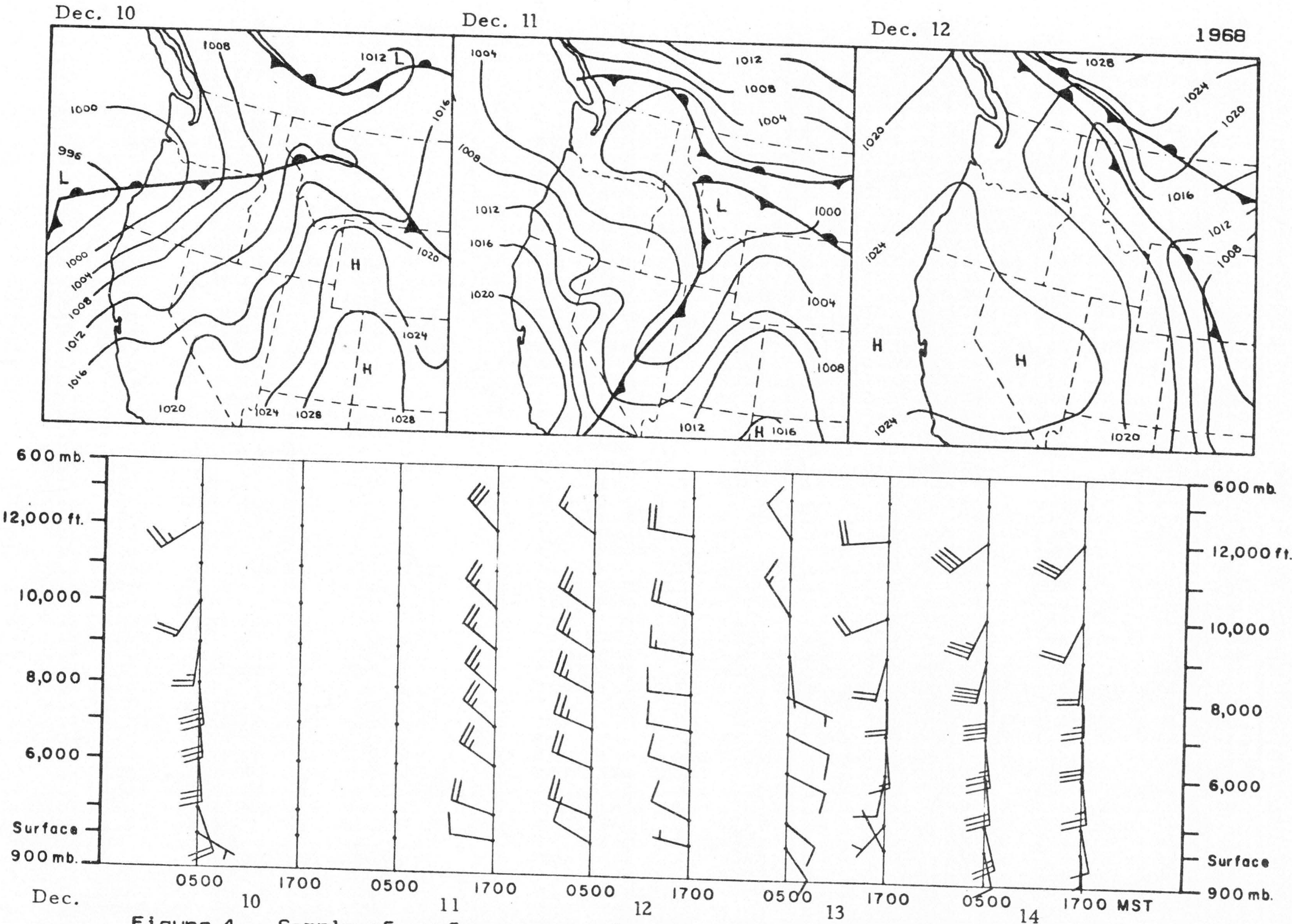


Figure 4. Sample of surface maps and vertical time cross sections of winds used in the analysis of ice nuclei concentrations.

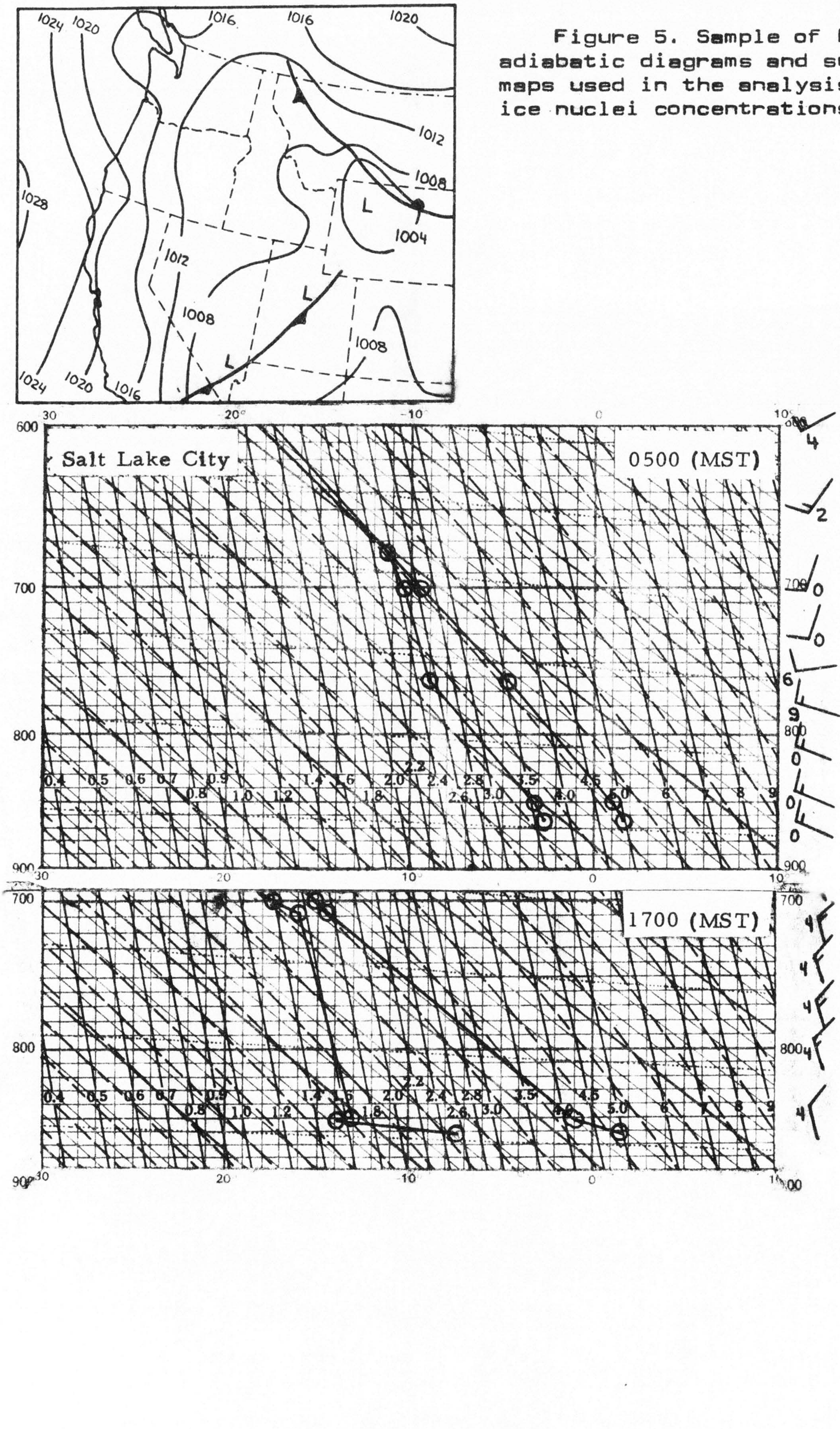


Figure 5. Sample of Pseudo-adiabatic diagrams and surface maps used in the analysis of ice nuclei concentrations.

The arithmetic mean, generally used, is greatly influenced by extreme values and is a questionable, or at least misleading, descriptive value (Slusser, 1968). For this reason the medians have also been calculated for all periods and were used in the statistical analysis of the data.

The standard deviation is used to estimate the degree of variability about the mean, but it is not an appropriate term to be used with the median. The sum of the squared deviations is least when computed about the mean; however, the sum of the absolute deviations is at a minimum when computed about the median. In this report the semi-interquartile range, or quartile deviation, q, defined by the equation

$$q = (Q_3 - Q_1)/2$$

where Q_1 and Q_3 are the first and third quartiles, is used to estimate the degree of variability about the median ($\tilde{x}$).

Absolute measures of variability are useful in helping to understand a particular set of observations, but do not give a complete picture of the variability. They are of little value for comparing observations taken at several different localities. This is due to the fact that variability generally increases as the values of the observations become larger. For this reason, the relative variability, Vq, defined by the equation

$$Vq = \frac{100\ (Q_3 - Q_1)}{2\ \tilde{x}}$$

is used to derive comparable figures. The Mahalingam interval, M, is used to give significance levels (Lackey, 1942). The formula for determining the limits of the M interval is:

$$L = \tfrac{1}{2}\left[(N + 1) \pm K\sqrt{N}\right]$$

where L indicates the positions in the array of ordered observations of the upper and lower values of the M interval, N is the number of observations, and K is the constant which depends on the significance level used (i.e. 1.65 for the 5 percent level and 2.32 for the 1 percent level).

A non-parametric test, the Friedman two-way analysis of variance by ranks, was used to determine if any diurnal variations existed.

Rawinsonde data from Salt Lake City and Cache Valley soundings were used in an attempt to relate nuclei concentrations to meteorological parameters. Ice nuclei concentrations during background, seeded, and nonseeded (buffer) periods were plotted against temperatures and wind directions at the 500 mb, 700 mb, and 850 mb levels. Ice nuclei concentrations were also plotted against cloud base and cloud top temperatures and surface pressure. These plots, or scattergrams, did not indicate relationships close enough to warrant the use of statistical tests.

Background counts

Background counts have been divided into three classes for purposes of analysis and discussion: 1) measurements taken on days without precipitation were classified as non-precipitation weather (hereafter referred to as NPW) concentrations; 2) counts taken on days with precipitation from minor disturbances were classified as precipitation weather (hereafter referred to as PW) concentrations; 3) measurements taken during the first period of an eight hour experimental event which was seeded during the second half were classified as nonseeded first (hereafter referred to as NS1 concentrations.

To be considered a background count a measurement must not have been taken within a period of thirteen hours following the release of artificial ice nuclei. Measurements taken during periods of up to 24 hours following a seeded event were also excluded if large concentrations of residual nuclei (from seeding) were in the area.

Two classes of nonbackground nuclei will also be referred to: 1) measurements taken during seeding operations which were classified as seeded (hereafter referred to as S) concentrations; and, 2) measurements taken during the second half of an eight hour experimental event which were classified as nonseeded second (hereafter referred to as NS2) concentrations.

RESULTS AND DISCUSSION

Background Counts--Spatial and Temporal Variations

The purpose of this section is twofold: 1) to establish the natural background ice nuclei count as a basis for judging whether or not the addition of artificial ice nuclei is needed to optimize precipitation amounts under various meteorological conditions; and, 2) as a basis for judging whether or not effluent released during seeding operations is coming down into Cache Valley during seeding operations. Spatial and temporal variations in ice nuclei concentrations will also be discussed although those for Cache Valley were somewhat discussed above (see p. 19).

Cache Valley

Counts taken during the 1968-1969 season are presented in Appendix I. Table 2 lists the days and the hours during which observations for each of the three classes of background ice nuclei concentrations were measured at the various stations.

Ice nuclei distributions are presented in Figure 6. Concentrations are shown to differ significantly from year to year, and in most cases, from month to month. NPW concentrations have the largest ranges, median, absolute variations, and relative variations. This would be expected

Table 2. Ice Nuclei Sampling Periods--Cache Valley.[a]

Class Date	Time	Sampling Locations[b]	Volume Sampled (Liters)	Number of Samples
NPW				
Dec 1968				
8	1302-1708	CV	600	30
13	1540-2000	HP	2600	26
16	1810-2400	HP	3500	35
17	0000-2400	HP	14400	144
18	0000-2400	HP	14400	144
19	0000-2400	HP	14400	144
20	0000-1100	HP	6600	66
31	1800-2400	HP	3600	36
		For Month	60100	625
Jan 1969				
1	0000-1300	HP	7500	75
2	1800-2400	UWRL	3600	36
3	0000-1800	UWRL	10800	108
14	1840-2400	NL	3200	32
15	0000-1900	NL	11400	114
		For Month	36500	365
Feb 1969				
4	1030-1630	UWRL	3600	36
7	1456-1550	CV	300	15
8	1050-1300	HP	1400	14
14	0600-2000	Avon	8400	84
23	0600-2400	HP	10800	108
24	0920-1208	CV	900	45
24	1000-2400	PAR	8400	84
26	0700-1130	PAR	2700	27
26	1250-1850	CV	2000	100
27	0000-0800	Mill	4800	48
28	0600-2000	Mill	8400	84
28	1000-2200	CV	2400	120
		For Month	54100	729
Mar 1969				
7	1200-2400	HP	7200	72
7	1420-2115	CV	1500	75
8	0000-1700	HP	10200	102
21	1000-1830	HP	5100	51
		For Month	24000	300
Apr 1969				
3	1340-0000	UWRL	6200	62
4	0000-1620	UWRL	9700	97
9	0000-1500	UWRL	9000	90
10	1630-2400	UWRL	4500	45
11	0000-1400	UWRL	8400	84
		For Month	37800	378
		YEARLY TOTAL	212500	2397

Table 2. Continued

Class Date	Time	Sampling Locations[b]	Volume Sampled (Liters)	Number of Samples
NPW (Continued)				
Nov 1969				
5	0610-1650	CV	2900	145
5	1650-2400	HP	4300	215
6	2400-1700	HP	10200	510
8	1100-1430	CV	1100	55
8	1500-2400	HP	5400	270
9	0000-1500	HP	9000	450
17	0800-1500	CV	2400	120
17	1600-2400	HP	4800	240
18	0000-1600	HP	9600	480
22	0408-2400	HP	11920	596
23	0000-0940	HP	5800	290
26	0800-2400	UWRL	9600	480
27	0000-0800	UWRL	4800	240
		For Month	81820	2091
Dec 1969				
4	1200-2400	CV	2700	135
5	0000-0430	CV	2000	100
6	1900-2400	CV	1300	65
7	0000-0800	CV	2400	120
13	0400-2400	HP	12000	600
14	0000-2400	HP	14400	720
		For Month	34800	1740
Jan 1970				
23	0430-0800	CV	1200	60
Feb 1970				
4	1830-2400	HP	3300	165
5	0000-0930	HP	5700	285
		For Month	9000	450
Mar 1970				
15	1200-2400	UWRL	7200	360
		YEARLY TOTAL	134020	6701
PW				
Jan 1969				
22	0900-2400	HP	9000	90
23	0000-1800	HP	10800	108
26	1500-2400	HP	5400	54
27	0000-1010	HP	6100	61
		For Month	31300	313

Table 2. Continued

Class Date	Time	Sampling Locations[b]	Volume Sampled (Liters)	Number of Samples
PW (Continued)				
Feb 1969				
6	0000-1520	UWRL	9200	92
24	0000-1000	HP	6000	60
25	0000-1000	PAR	6000	60
26	2020-0000	Mill	2200	22
		For Month	23400	234
Apr 1969				
7	1130-2400	UWRL	7500	75
8	0000-2400	UWRL	14400	144
		For Month	21900	219
		YEARLY TOTAL	76600	766
Nov 1969				
15	0800-2400	HP	9600	480
16	0000-0800	HP	4800	240
		For Month	14400	720
Dec 1969				
23	1220-2300	HP	6400	320
Jan 1970				
11	0100-1200	HP	6600	330
Feb 1970				
3	1430-2230	HP	4800	240
16	2230-2400	HP	900	45
17	0000-0710	HP	4300	215
		For Month	10000	500
Mar 1970				
29	0200-1300	HP	6600	330
Apr 1970				
15	2200-2400	HP	1200	60
16	0000-2200	HP	13200	660
		For Month	14400	720
		YEARLY TOTAL	58400	2920
Dec 1970				
10	0000-1000	HP	6000	300
22	0700-1040	HP	2200	110
		For Month	8300	410
Feb 1971				
2	1900-2400	HP	3000	150
3	0000-1900	HP	11400	570
27	1400-2400	HP	6000	300
28	0000-1400	HP	8400	420
		For Month	28800	1440

Table 2. Continued

Class Date	Time	Sampling Locations[b]	Volume Sampled (Liters)	Number of Samples
PW (Continued)				
Mar 1971				
29	1500-2400	HP	5400	270
30	0000-0800	HP	4800	240
		For Month	10200	510
Apr 1971				
19	1800-2400	HP	3600	180
20	0000-2400	HP	14400	720
21	0000-1800	HP	10800	540
		For Month	28800	1440
		YEARLY TOTAL	76000	3800
NPW	ALL YEARS TOTAL		346,520	9,098
PW	ALL YEARS TOTAL		211,000	7,486

[a]NSl Values given in Tables 4 and 5.

[b]Location Code given in Table 1, p. 17.

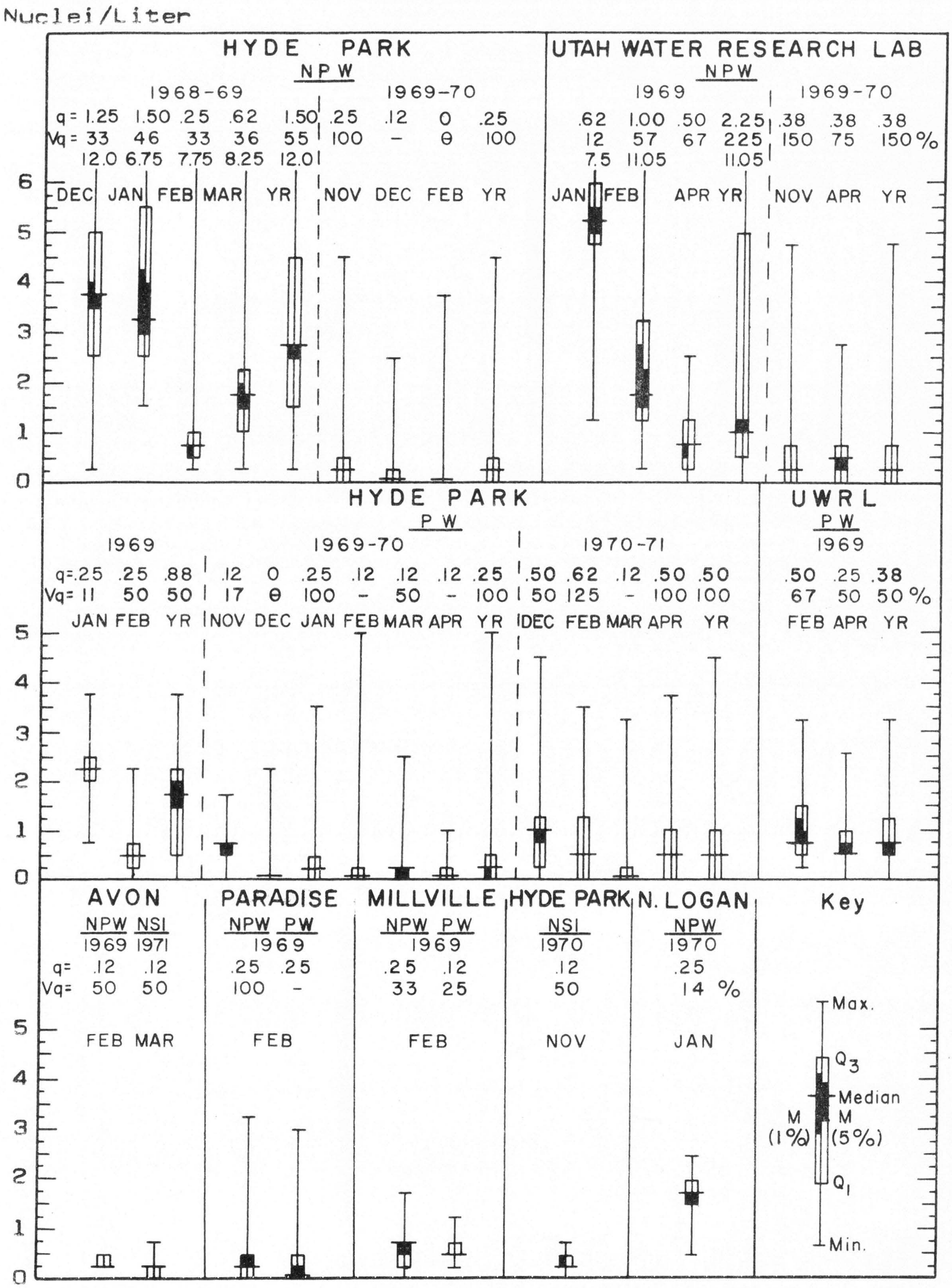


Figure 6. Background ice nuclei distributions during precipitation weather (PW), nonprecipitation weather (NPW), and experimental periods (NSI).

since the meteorological conditions under which these occur offer the greatest opportunity for the buildup of large nuclei concentrations. The lower PW concentrations occur during disturbances which are apparently strong enough to produce some cleansing of the Valley. The NS1 concentrations should be the lowest since these occur during fairly intense storms lasting eight hours or longer. While observations of NS1 concentrations are available for only two periods in the Valley, Figure 6 does show that they are in fact very low with no observation exceeding .75 nuclei per liter (70 percent of the values were equal to or smaller than .25 per liter).

Even though ice nuclei concentrations were high during the 1968-1969 season when compared to those observed during the following years, they are quite compatible with the values reported for the Colorado Mountains (Reinking and Grant, 1967 and 1968, Grant et al, 1968, and Rhea et al, 1969); for Washington and Wyoming (U.S. Bureau of Reclamation, 1969); and for Antarctica, Australia, Hawaii, Sardinia, and England (Bigg as reported by Crozier, 1969b). They are somewhat lower than the late summer values Battan and Riley (1960) reported for maritime air at Mount Bigelow (Arizona).

Figure 7 compares PW concentrations for Hyde Park with those reported by Reinking (1970) for the Colorado Rockies. Hyde Park concentrations are consistently smaller with the

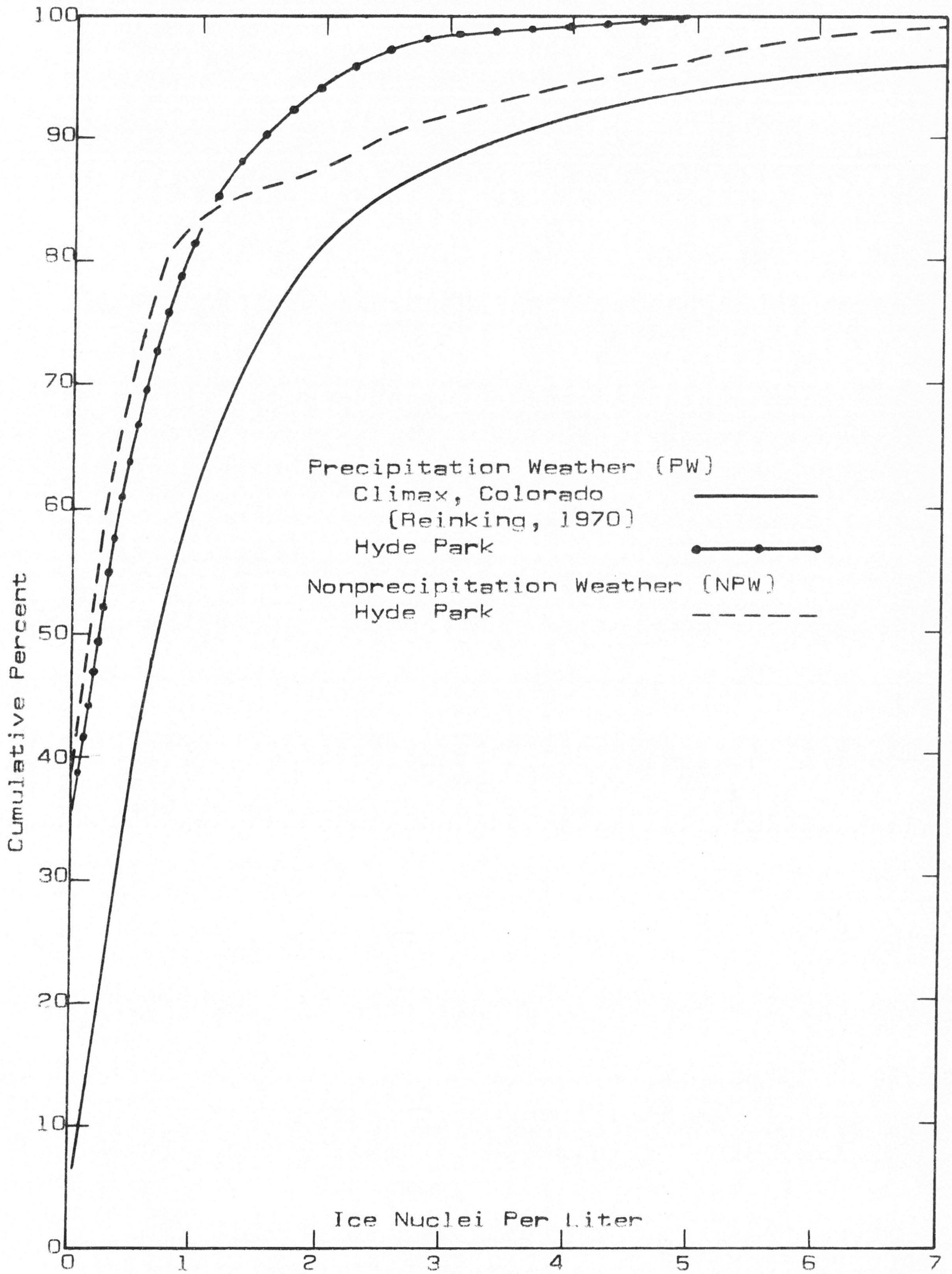


Figure 7. Cumulative percent of ice nuclei observations as a function of nuclei concentration measured at -20 C for the indicated background periods and locations.

median being one-third those reported for the Rockies, and the variability is also much less at Hyde Park. Reynolds and Slusser [1970] reported an apparent seasonal trend in ice nuclei concentrations with a decrease from December through April. In their study background counts were not grouped into classes as in the present study and mean values for all stations were combined. They were also limited to data from the 1968-1969 experimental season. In the present study there is still an indication of a seasonal trend during the 1968-1969 season [Figure 6]. Figure 8 represents the distributions obtained when data from all three years are combined. As can be seen, there is no indication of a seasonal trend in any group. There was also no indication of a seasonal trend at other stations.

The data were examined for evidence of diurnal variations in nuclei concentrations. Although there were definite, systematic, hour to hour changes in the number of nuclei these trends were not consistently related to the time of day [with the exception of those for April of the first year]. The April measurements were consistently higher during the hours of darkness, followed by a downward trend to a minimum during the early afternoon, followed by a rise beginning approximately 1600 or 1700 hours [see Appendix I]. Inter-diurnal variations at a station were no greater than the diurnal variations.

As mentioned previously, an attempt to determine the

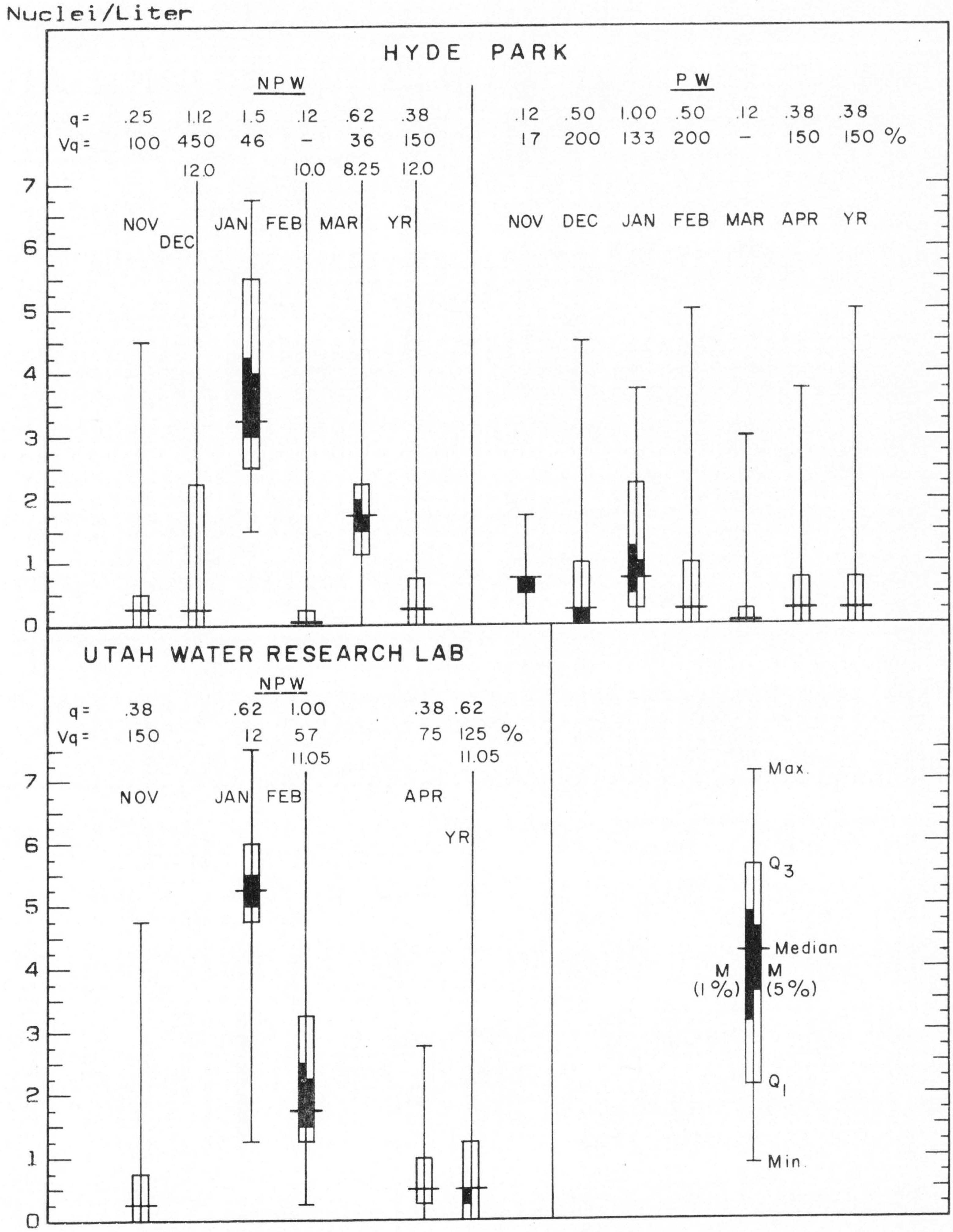


Figure 8. Background ice nuclei distributions during precipitation weather (PW) and nonprecipitation weather (NPW) 1968-1971.

spatial variations in ice nuclei concentrations which exist on a given day in the Cache Valley was discontinued due to the great temporal variations. It is, therefore, difficult to imply the existence of spatial variations in ice nuclei concentrations from data collected with the stationary counter. These counts were not taken at the same instant, or even during the same time periods on different days.

The data as collected indicate that nuclei concentrations do not differ noticeably over large areas of the Valley for a given time period. Figure 9 shows that although concentrations vary markedly for the same time periods on different days (or months) at all stations, there is little difference in ice nuclei concentrations between stations. The dominance of a southerly airflow from the Salt Lake City area may account for the large NFW concentrations of ice nuclei during the first year.

Salt Lake City

It has been suggested in the previous section that the Salt Lake City area may be a source of ice nuclei since high counts were recorded in the Cache Valley on days with southerly winds. Counts taken in the Salt Lake City area on ten days, using a fairly dense network of counting locations, showed that, indeed, there were sufficient nuclei in the Salt Lake City area to be an effective source of ice nuclei.

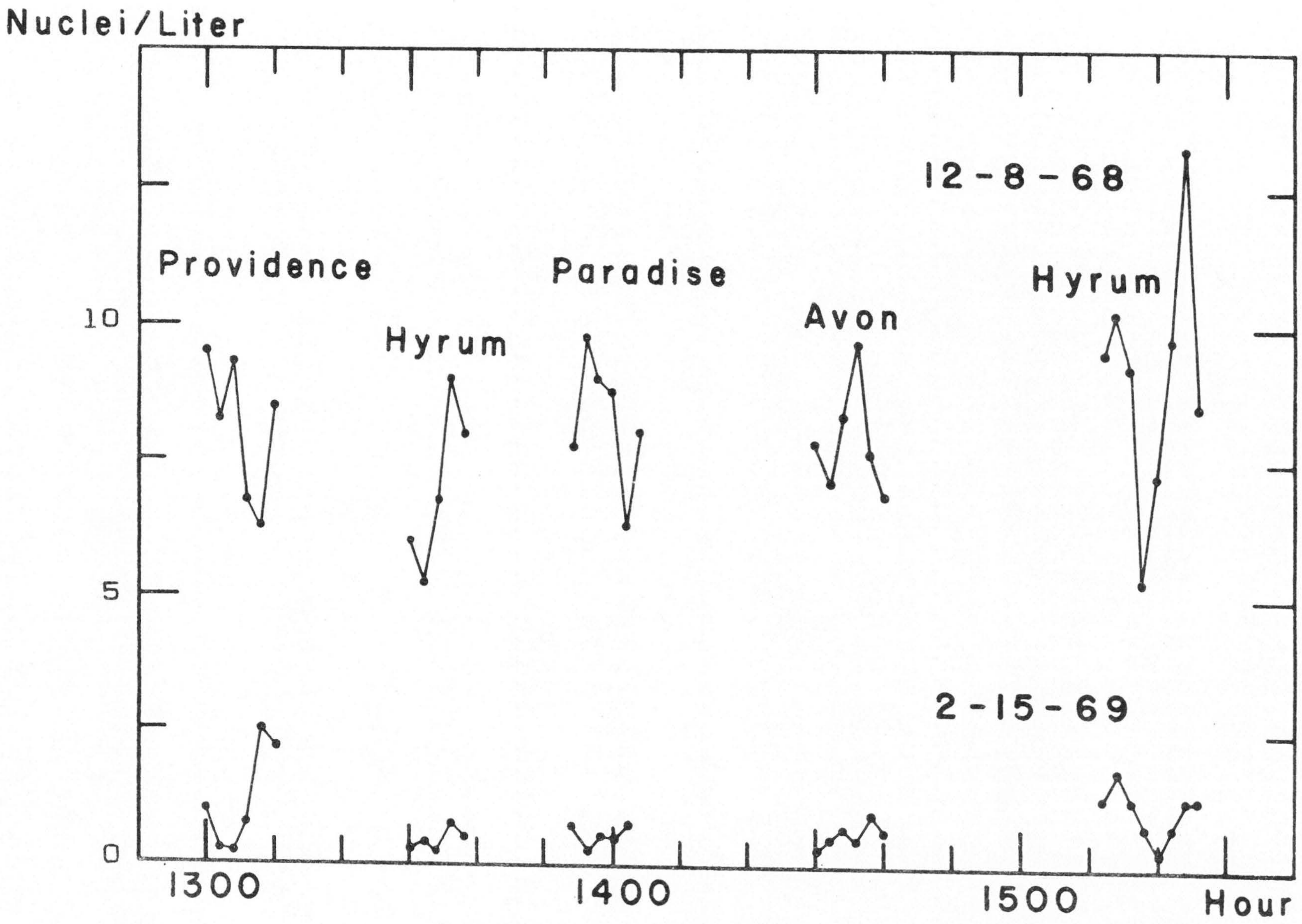


Figure 9. Ice-forming nuclei counts at the indicated places and times.

The data shows that the Garfield Smelters are a major source of ice nuclei. Reynolds (1970) reported that flights made over the area also show the Garfield Smelters to be a major source of ice nuclei. Concentrations as large as 6000 nuclei per liter were reported over the smelters while the highest concentration found at the surface was 400 nuclei per liter. Geneva Steel, located south of the Salt Lake City area on the north shore of Provo Lake, also contributes large quantities of ice nuclei to the Salt Lake City area.

Concentrations at the surface varied considerably according to the meteorological conditions. Ice nuclei concentrations are shown to be low in all areas with high wind speeds and absolute instability persisting throughout the day (Figure 10). Figure 11 shows that with very little or no wind and absolute stability persisting throughout the day, counts are high in all areas. Under these conditions nuclei released by the smelters do not seem to come down into the valley. The stacks are several hundred feet above the surrounding counting locations and the effluent does not move in a downward direction when there is a stable layer near the surface.

Highest concentrations were recorded on days when an inversion occurred from the surface to well above the tops of the stacks during the morning hours followed by absolute instability later in the morning (Figure 12). Under

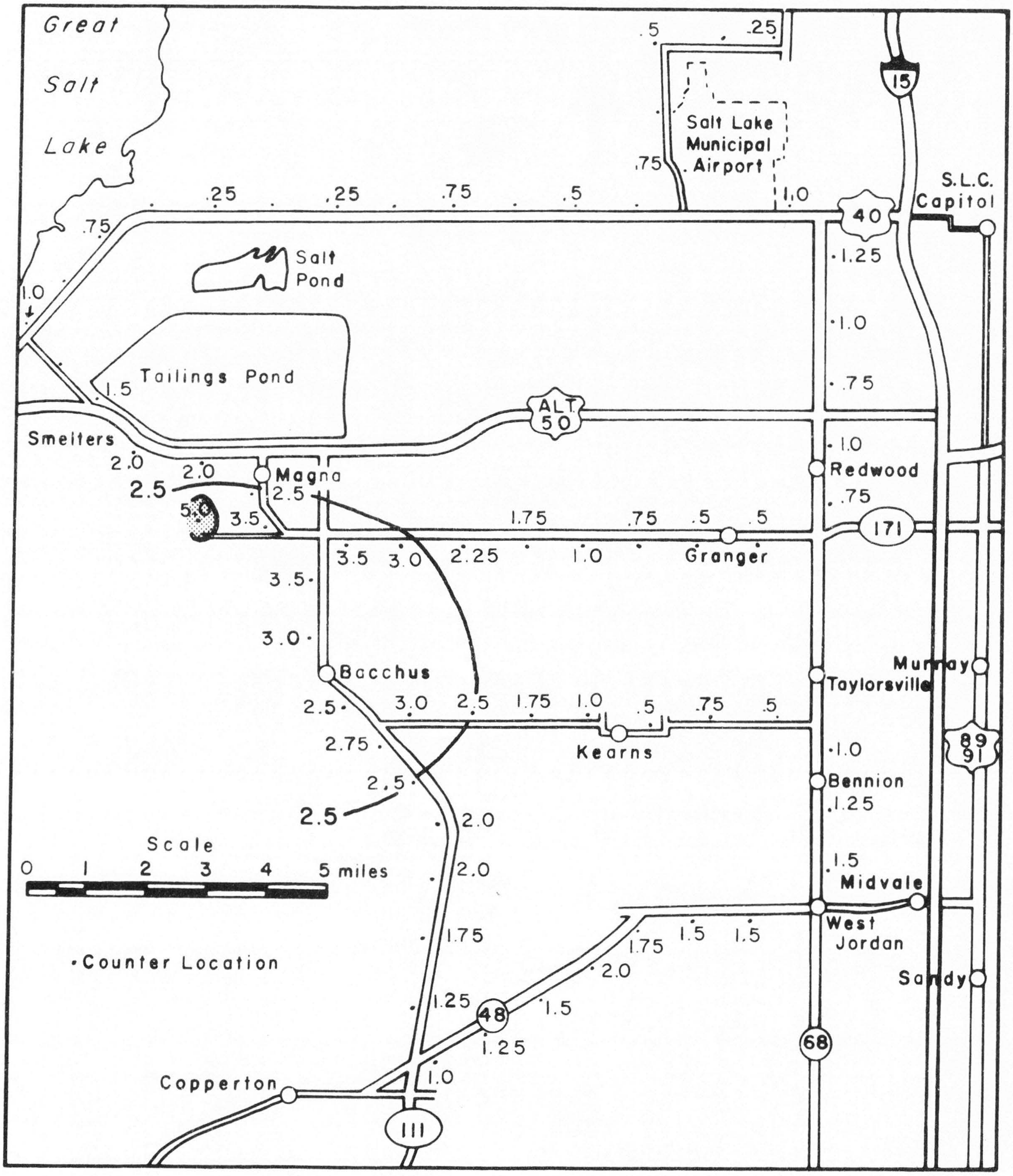


Figure 10. Median ice nuclei concentrations (nuclei/liter) in the Salt Lake City area on March 5, 1970.

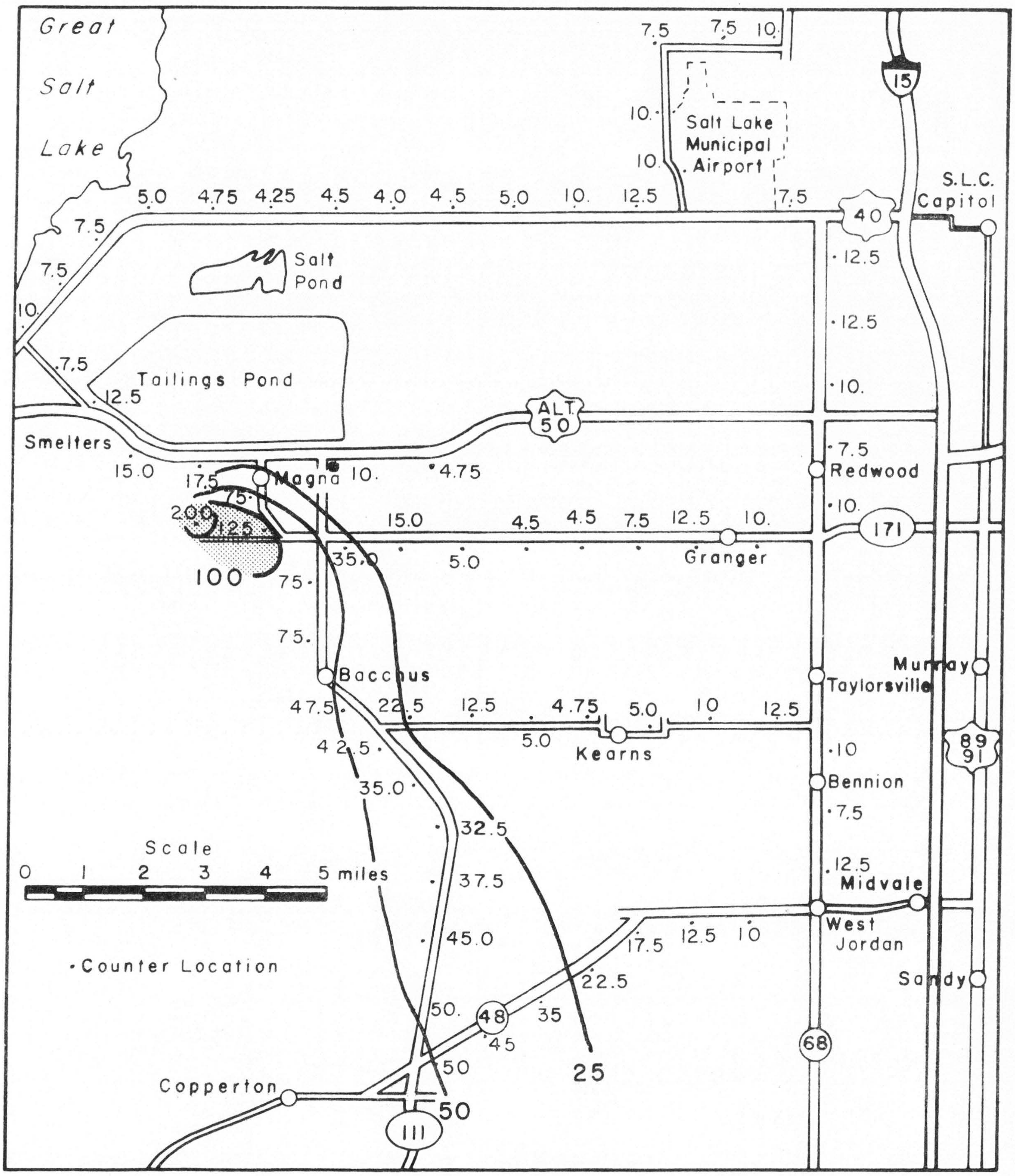


Figure 11. Median ice nuclei concentrations (nuclei/liter) measured in the Salt Lake City area on February 11, 1970.

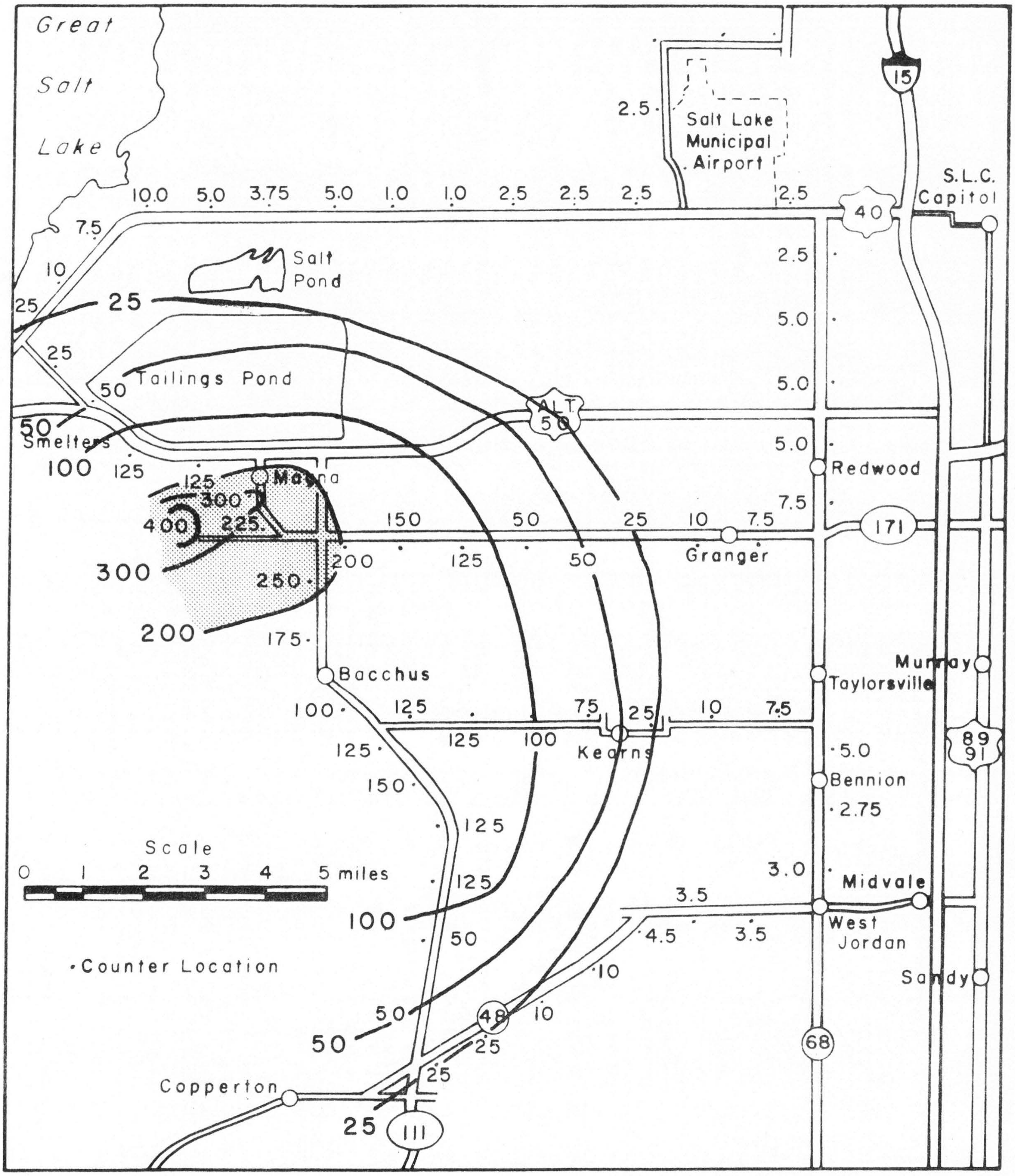


Figure 12. Median ice nuclei concentrations (nuclei/liter) measured in the Salt Lake City area on March 20, 1970.

these conditions the plume stays at a fairly constant elevation above the surface with very little dispersion horizontally or vertically as long as the inversion (or stable condition) persists. Later in the morning, as the surface begins to heat, an unstable layer of air forms at the surface. When this unstable layer reaches the level of the plume, the effluent is brought down to the surface and large concentrations of ice nuclei are recorded. With high southerly winds concentrations were found in the southern part of the study area indicating the source may be Geneva Steel (Figure 13).

In the Cache Valley where there seems to be no major localized source of ice nuclei, temporal variations masked the spatial variations. This problem did not exist in the Salt Lake City area on days when effluent from the smelters was able to reach the surface. Even though up to 10 hours were required to count at all locations, on only one day did significant temporal variations occur (Figure 14). This may have been due to a shift in wind direction, or, more probably, to counting which began before the unstable layer had fully developed and was not yet bringing down the larger concentration.

Experimental area

Measurements were made at various times in all parts of the experimental area that could be reached by car. During periods of prolonged high pressure associated with a domi-

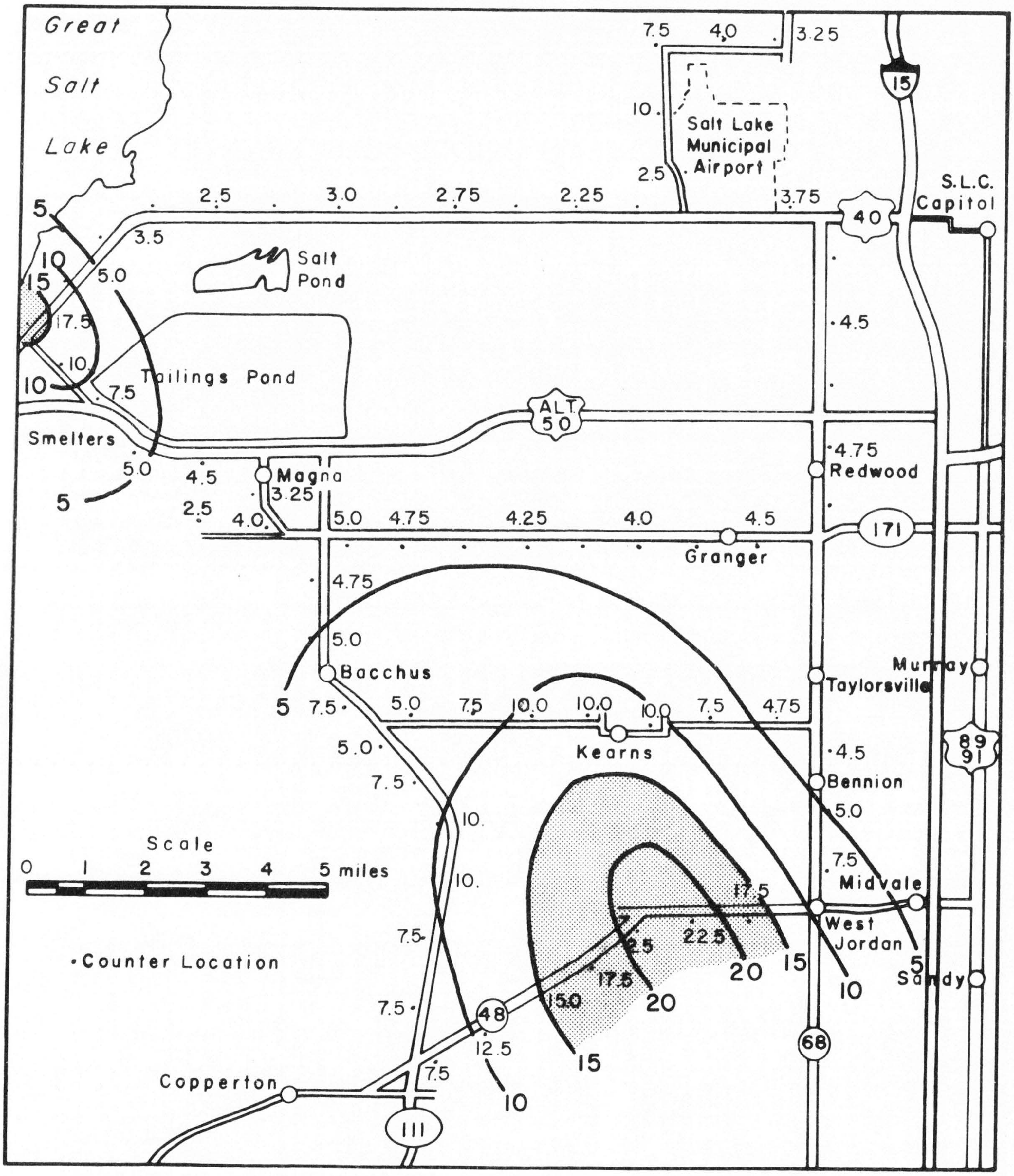
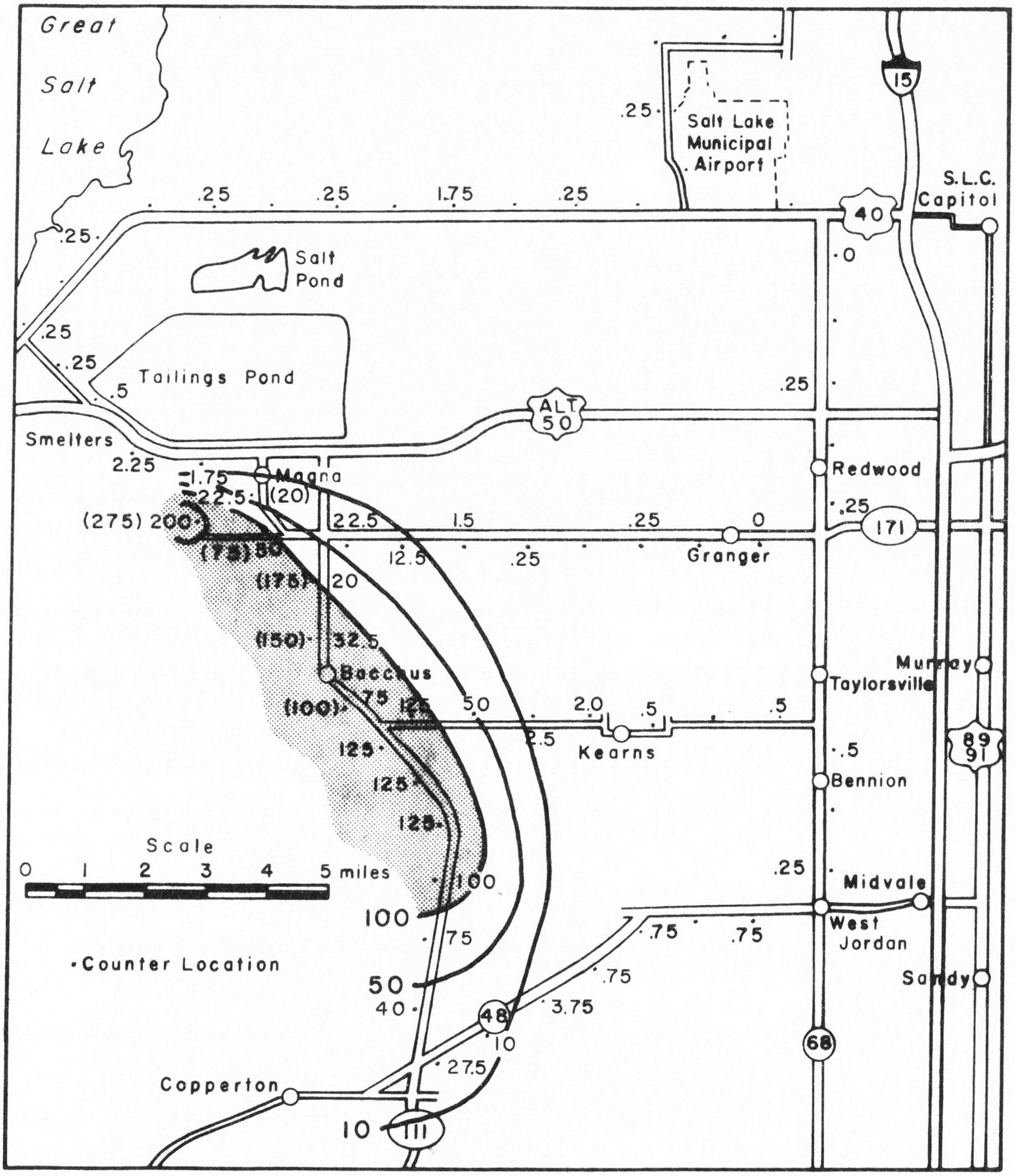


Figure 13. Median ice nuclei concentrations (nuclei/liter) for the Salt Lake City area on February 9, 1970.

Figure 14. Median ice nuclei concentrations (nuclei/liter) recorded in the Salt Lake City area on March 10, 1970.[a]



[a]Morning readings are given for all locations. Where temporal variations occur, afternoon readings are given in brackets.

nance of absolute stability, pollution from the Salt Lake City, Ogden, and Provo areas could be seen in the valleys and canyons near the Wasatch Front. Counts near 5 nuclei per liter were common in Ogden, Weber, and Provo Canyons and in the Heber Valley. Even areas as far away from a major source of pollution as Bear Lake Overlook had counts above 4 nuclei per liter. The maximum concentrations in the Ogden area were 25 nuclei per liter. On two separate occasions concentrations as large as 1750 nuclei per liter were recorded at the top of the haze layer near Kaysville. Winds were light from the Southeast, indicating the Garfield Smelters as a possible source. Auto exhaust could also be a major contributor (Langer, 1969a, p.3).

Figure 15 represents the distributions of background ice nuclei counts for stations outside the Cache Valley which were also used during experimental events. Table 3 lists the days and times during which counts were taken. Again the NPW concentrations are the highest and the NS1 concentrations the lowest for the same reasons stated in the Cache Valley section. There are no seasonal trends evident. Distributions differ significantly (at the 5 percent level) from station to station during most months for which data is available. Concentrations recorded at the lowest station, Hardware Ranch, have the largest medians and greatest variabilities. The lowest values are not found at the highest station (Bear Lake Overlook), but at

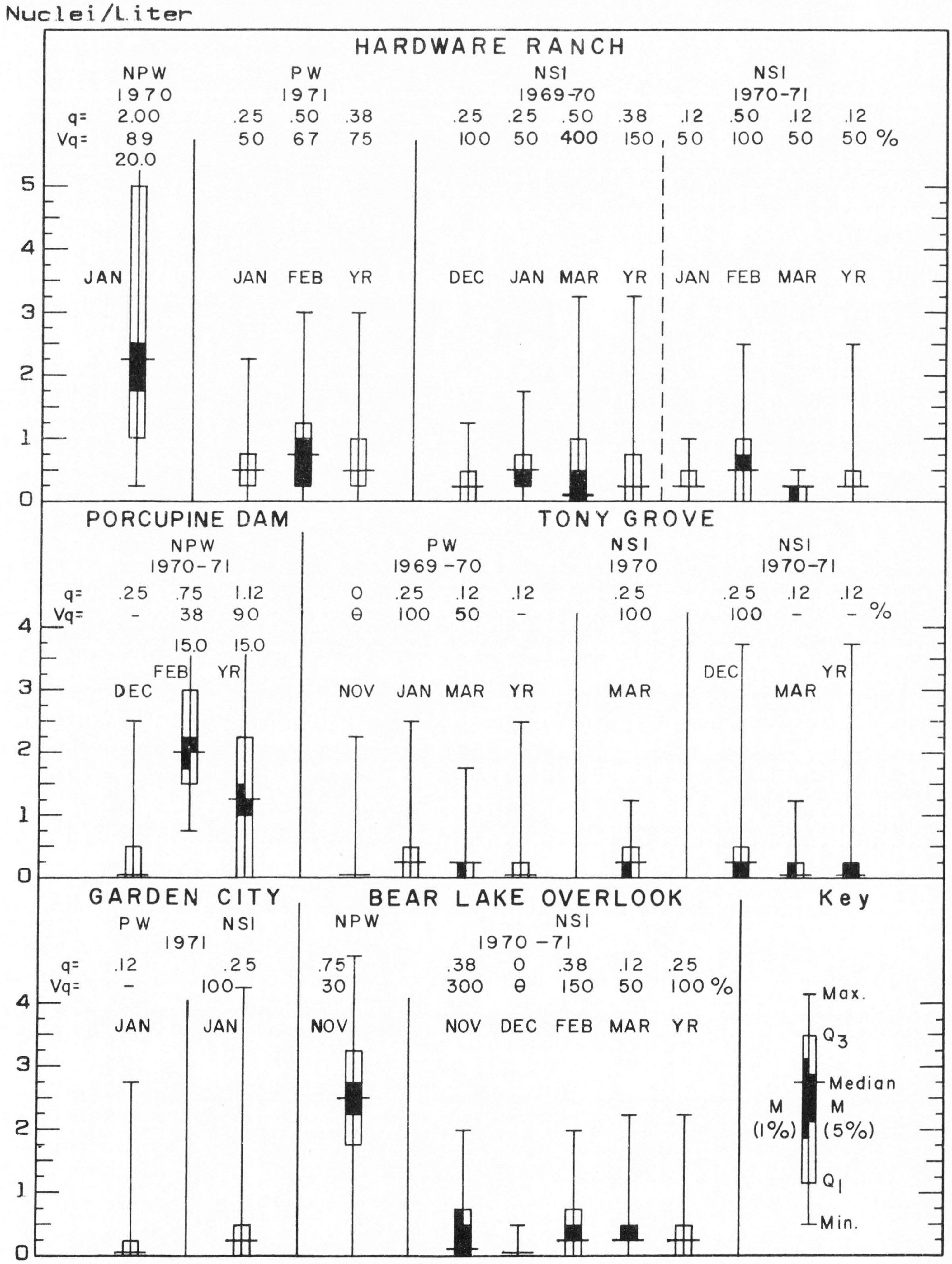


Figure 15. Background ice nuclei distributions during precipitation weather (PW), nonprecipitation weather (NPW) and experimental events (NSI).

Table 3. Ice Nuclei Sampling Periods--Experimental Area

Class	Date	Time	Sampling Locations[a]	Volume Sampled (Liters)	Number of Samples
NPW	Jan 1970				
	23	1330-1730	HR	2400	120
	24	1300-1800	TG	3000	150
		Total 1969-1970		5400	270
	Nov 1970				
	19	0800-1150	BLO	3480	174
	Dec 1970				
	4	0900-1700	PD	4800	240
	Feb 1971				
	2	0930-1730	PD	4800	240
		Total 1970-1971		13080	654
		Total 1969-1971		18480	924
PW	Jan 1970				
	14	1930-2330	TG	2400	120
	Feb 1970				
	12	2000-2300	TG	1800	90
	13	1400-2400	TG	6000	300
	14	0000-0100	TG	600	30
		For Month		8400	420
	Mar 1970				
	8	1000-1500	TG	3000	150
	25	2300-2400	TG	600	30
	27	0000-1120	TG	6800	340
		For Month		10400	520
		Total 1969-1970		21200	1060
	Nov 1970				
	13	0100-1000	TG	5400	270
	Jan 1971				
	9	2230-2400	HR	900	45
	10	0000-0630	HR	3900	125
	13	1000-1500	GC	3000	150
		For Month		7800	390
	Feb 1971				
	5	1000-1400	HR	2400	120
	10	1000-1200	HR	1200	60
	24-25	2330-0030	HR	600	30
		For Month		4200	210
		Total 1970-1971		17400	870
		GRAND TOTAL		38600	1930

[a]Location Code given in Table 1, p. 17.

Tony Grove. The higher reading at Bear Lake Overlook may indicate that nuclei are being caught in rotors since this station is on the lee side of the Mountains.

Figure 16 compares the PW and NS1 concentrations with those found by Reinking [1970] in the Colorado Rockies. As shown, concentrations in the experimental area are lower.

Measurements of ice nuclei concentrations taken in the Wasatch Weather Modification Experimental Area are shown to be considerably below optimum levels which, according to Reinking and Grant [1968], should be at least 10 to 20 nuclei per liter. Evidence is given for the need to seed storms with cloud top temperatures in the -12 to -26 C range to optimize precipitation amounts.

Ice Nuclei Measurements During Experimental Events

Ground seeded events

Dates, times, and locations of ice nuclei sampling are presented in Table 4 for experimental events during which seeding was accomplished by the release of silver iodide from ground based generators. Also listed for the second and third years is the half of the 8 hour experimental event during which seeding occurred.

Figure 17 illustrates the distributional features of the nuclei concentrations for the various stations and time periods. Ten minute average concentrations are

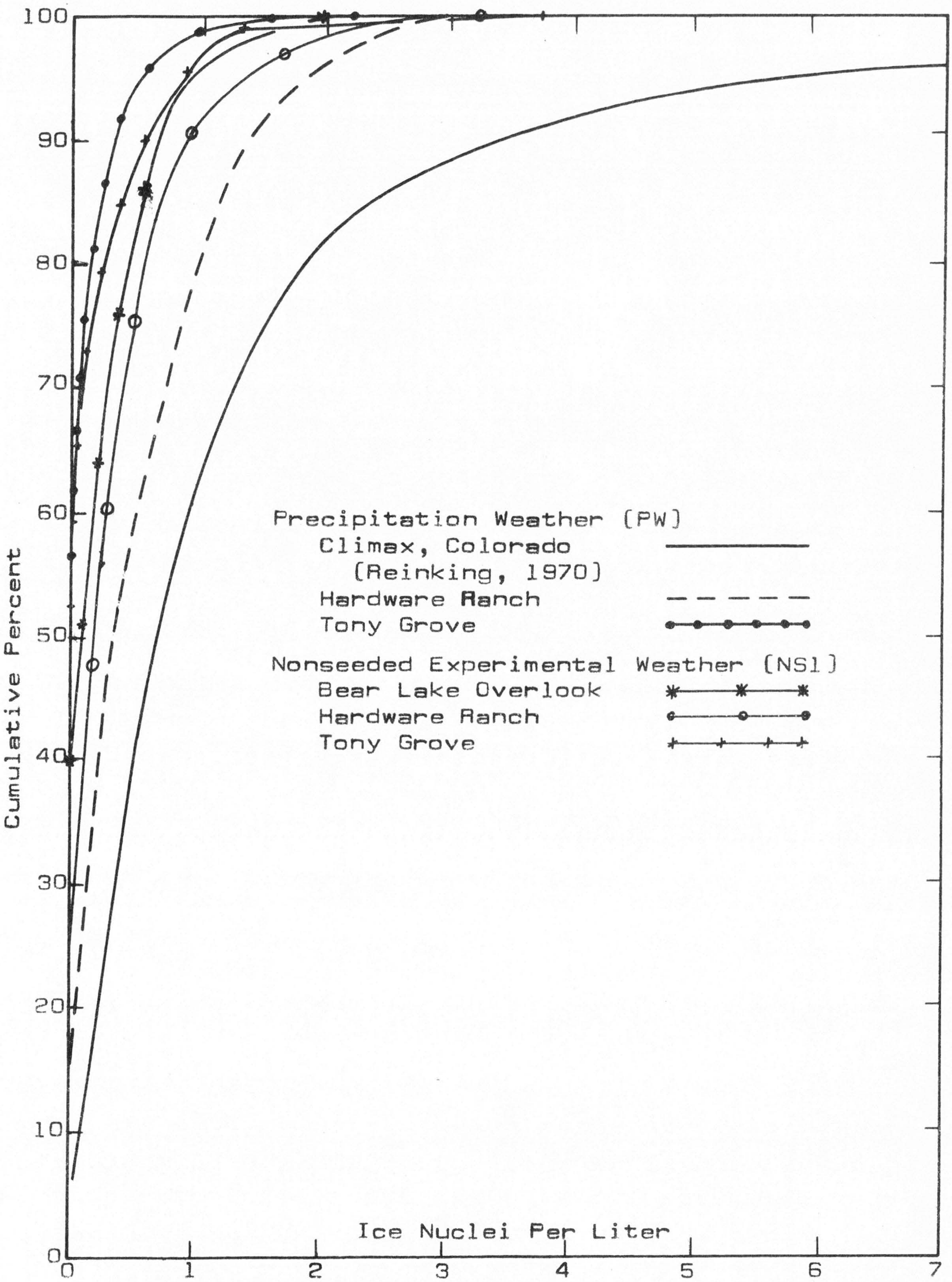


Figure 16. Cumulative percent of ice nuclei observations as a function of nuclei concentration measured at -20 C during the indicated background periods.

Table 4. Ground Seeded Experimental Events[a]

Date	Experimental Event	Seeded Half	Seeded Site	Counting Period	Counting Site	Volume Sampled (Liters)	Number of Counts
1969							
Jan 21-22	1610-2010	--	BCE	1950-0910	HP	7500	75
Feb 4-5	1630-1130	--	BH	1630-1230	UWRL	12000	120
12-13	0815-1700	--	BH	1230-0030	UWRL	7200	72
13-14	0820-1700	--	BH	0820-0600-	Avon	13000	130
				1523-1811	CV	600	30
15-16	1630-2400	--	BH	2030-1130	HP	9000	90
				1428-1930	CV	1000	50
16-17	1130-1530	--	BH	1130-0430	HP	10200	102
21-22	1545-2300	--	BH	1540-1200	HP	12200	122
				1545-1918	CV	1400	70
25-26	0955-1800		BCE	1000-0700	Par	12600	126
				0758-1840	CV	1800	90
27-28	0800-1700	--	BCE	0800-0600	Mill	13200	132
				0923-2240	CV	3400	170
Mar 6-7	1500-2300	--	BCE	1800-1200	HP	10800	108
				1523-2115	CV	1600	80
1970							
Jan 2	1030-1830	1	WM	1030-2030	Morgan	6000	300
22	1230-2030	1	WM	1230-2030	HR	4800	240
Feb 1	0200-1000	2	WM	0210-1010	CV	3600	180
3-4	2230-0630	2	WM	2230-1830	CV	6800	340
17	0700-1500	2	WM	0700-1500	CV	3500	175
Mar 1	0830-1630	1	WM	0830-1830	Morgan	6000	300
Nov 6	1030-1830	1	WM	1030-1830	HR	4800	240
12-13	0900-1700	1	WM	1000-0100	TG	9000	450
18-19	1000-1800	2	WM	1300-0600	BLO	10200	510

Table 4. Continued

Date	Experimental Event	Seeded Half	Seeded Site	Counting Period	Counting Site	Volume Sampled (Liters)	Number of Counts
Nov (Continued)							
25	1200-2000	2	WM	1200-2000	HP	4800	240
25-26	2000-0400	2	WM	2000-1200	TG	9100	455
29	1400-2200	1	WM	1430-2400	HR	5700	285
29-30	2200-0600	2	WM	0200-0700	HR	3600	180
30	0600-1400	1	WM	0600-1600	HR	4800	240
30	1400-2200	1	WM	1400-2400	HR	6000	300
Dec 1	1000-1800	1	WM	1100-1900	HP	4800	240
1971							
Mar 4	1500-2300	2	WM	1500-2300	Avon	4800	240

[a]Location Code given in Table 1, p. 17 for all sites.

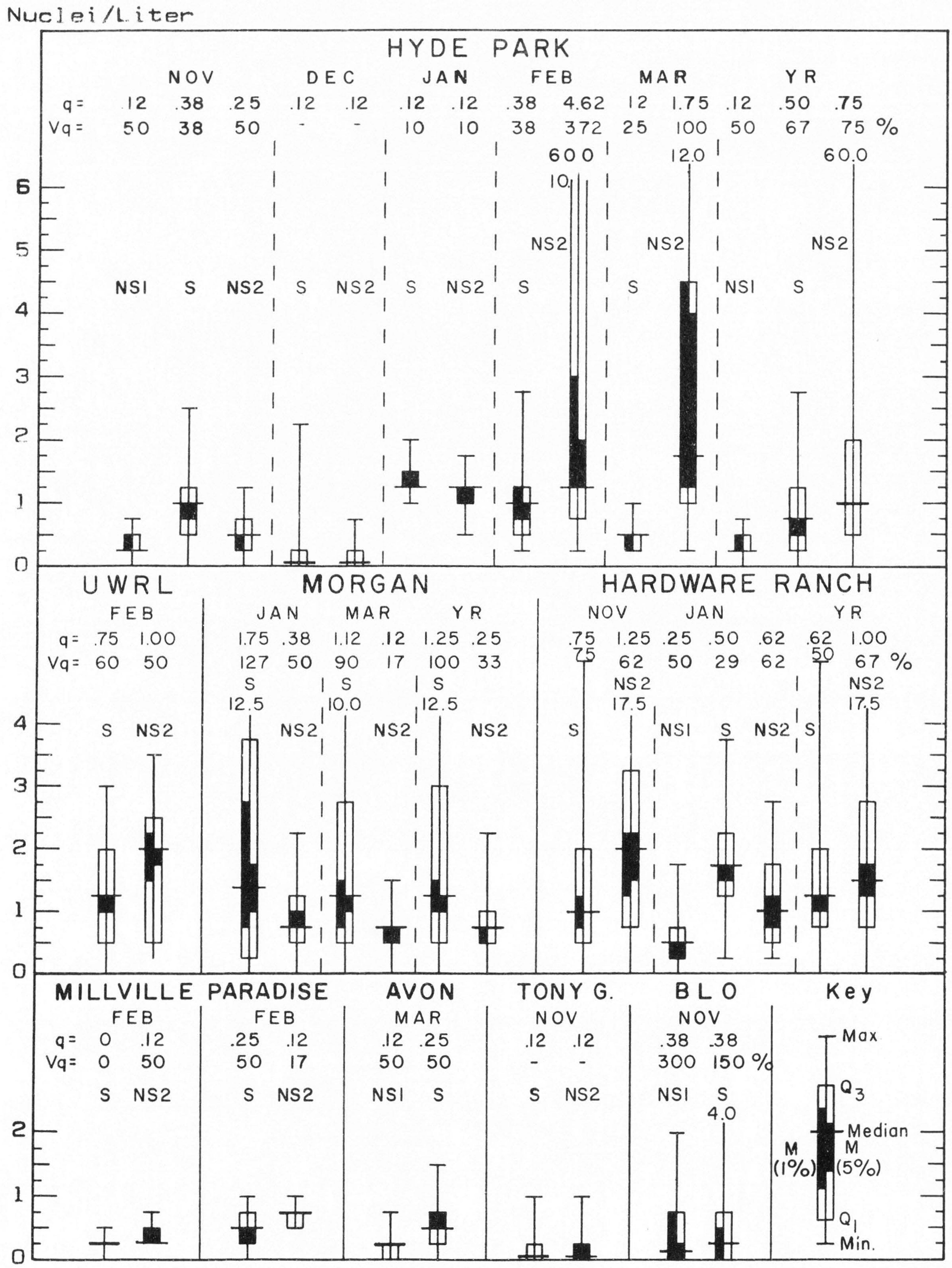


Figure 17. Ice nuclei distributions during seeded (S), nonseeded first (NS1), and nonseeded second (NS2) halves of experimental events.

presented in Appendix II for all events.

With few exceptions, median ice nuclei concentrations measured at the surface during the 4 hour period following the seeded period were as large as or larger than they were during the actual seeded period (at the 1 percent significance level). This is true even though a 2 hour lag period was used. The meximum concentrations and variances are also found during the period following rather than during the seeded period.

A study of the 10 minute average counts in Appendix II indicates that on the average, 1.4 hours lapse from the start of the seeding period to the time when increases in ice nuclei concentrations are experienced at the counter location. An average of 7.5 hours lapse after seeding is stopped to the time there are no longer any indications of residual ice nuclei. All indications are that the 2 hour buffer period now in use is insufficient. This will be discussed further (see p. 67).

During the second and third years when the 8 hour experimental period was in use, ratios were calculated using the total number of nuclei counted during the given 4 hour period. At the higher Tony Grove and Bear Lake Overlook stations S/NS1 and S/NS2 values were 1.5 and 0.8 respectively. The ratio S/NS1 indicates that ice nuclei released from ground based generators is reaching these stations. At the lower Hardware Ranch station S/NS1 and S/NS2 values were 0.6 and 0.8 respectively. The S/NS1 ratio for all Valley stations was 0.15.

The low S/NS2 value at the high elevation stations can be explained by the fact that effluent was reaching these areas in higher concentrations during the nonseeded period. This may be a partial explanation for the low S/NS2 values found at the lower elevation stations. Also, at the low elevation stations, the low S/NS1 and S/NS2 values may reflect temporal fluctuations in background concentrations. This is a real possibility since ice nuclei concentrations were low and there were only 4 samples.

The very low ratios and actual ice nuclei concentrations found in the Cache Valley indicate that the ice nuclei released from the Willard Mountain ground based generator are not being channeled down into the Valley and are not being trapped during seeded periods. Data for the first year indicate that nuclei released from the lower Blue Hill seeder site may be getting into the Valley. These large concentrations measured during seeding do not last for exceptionally long periods and may even be due to natural fluctuations in background ice nuclei concentrations. Comparing counts taken following seeding on February 22, 1969 with those on December 18, 1968 showing background counts, substantiates this last statement (see Appendix I and II).

Perhaps the most significant result obtained from the analysis of data gathered during the ground seeded events is partially illustrated by Figure 18. February 27, 1969 was one of the few days on which large concentrations of ice nuclei were found in the Valley for a prolonged period of time. The pattern shown in Figure 18 leaves little doubt that the high counts represent ice nuclei released by the ground based generator. The area was under the influence of a high pressure cell centered over Montana. Salt Lake rawinsonde showed absolute stability existing at nearly all levels during both morning and evening hours. Winds ranged from 0 to 10 knots at seeder level. The afternoon sounding showed a layer of instability from the surface to slightly below the seeder elevation which would aid in the downward transport of ice nuclei. Skies were cloudless. The purpose of this experimental event was to study plume behavior through the use of airborne nuclei counters to give some indication of occurrences during seedable events. It became obvious that plume behavior is not the same during clear and precipitation conditions.

Airborne seeded events

Appendix III contains 10 minute average ice nuclei concentrations taken during experimental events for which airborne generators were used to deliver silver iodide into the clouds. Dates, times, and the station at which measurements were taken are listed in Table 5. Quartiles, variances,

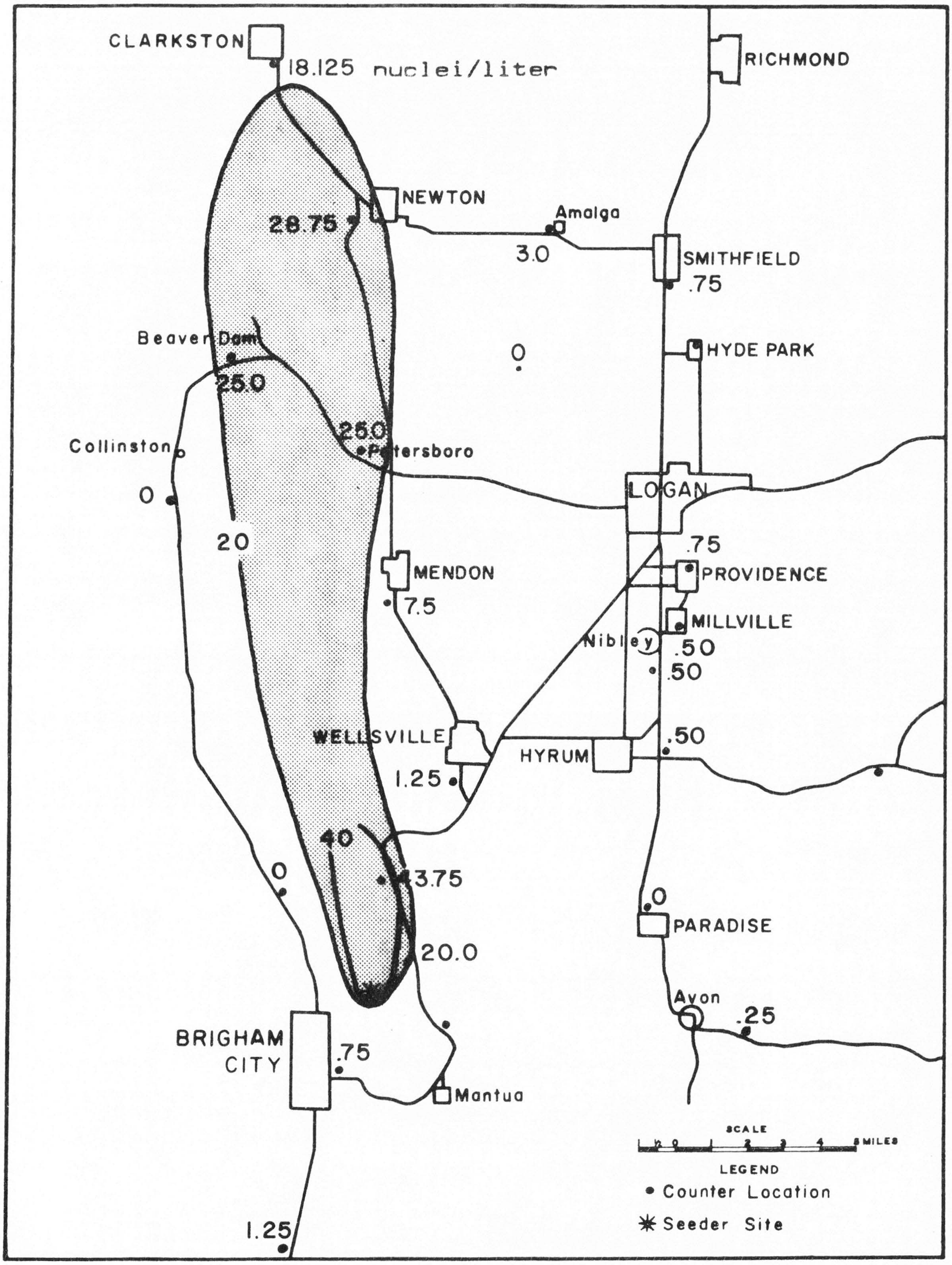


Figure 18. Concentrations of ice nuclei during a seeded event on February 27, 1969.

Table 5. Airborne Seeded Experimental Events

Date	Experimental Event	Seeded Half	Seeded Track	Counting Period	Counting Site	Volume Sampled (Liters)	Number of Counts
1969							
Dec 10-11	2300-0700	1	C3	2300-0900	TG	6000	300
19-20	2330-0730	1	B3	2330-0800	TG	5100	255
20-21	2300-0700	2	C2	2300-0900	HR	5400	270
21-22	2100-0500	1	B5	2100-1120	TG	7500	375
1970							
Jan 9-10	1700-0100	2	C5	1850-0800	HP/CV	5900	295
10-11	1100-1900	1	C4	0930-0200	TG	7800	390
16	1400-2200	2	B3	1430-2400	HR	5700	285
21	1230-2030	1	C3	1230-2030	TG	4800	240
21-22	2030-0430	1	C4	2100-0630	HR	5700	285
22	0430-1230	2	C3	0430-1430	HR	6000	300
27	1030-1830	1	B3	1030-1930	UWRL	5400	270
Feb 12-13	2300-0700	1	C4	2300-1400	TG	7800	390
14	0100-0900	1	C1	0100-1100	TG	6000	300
Mar 8	1100-1700	2	B2	1100-2200	HR	6600	330
14-15	2000-0400	1	C2	2000-1200	TG	9600	480
16-17	2300-0700	2	C3	2300-0710	HR	4900	245
28-29	1000-1800	1	C2	1000-0200	TG	9000	450
Dec 8-9	2300-0700	2	B4	2300-0800	TG	5400	270
9	0800-1600	1	B3	0800-2300	TG	9000	450
14-15	2330-0730	2	C3	2330-1530	BLO	9600	480
16	0930-1730	2	B5	0930-1730	TG	4800	240
18	0900-1700	1	B1	0930-1700	BLO	3900	195
21-22	1100-1900	2	A3	1100-0700	TG	11400	570

Table 5. Continued

Date	Experimental Event	Seeded Half	Seeded Track	Counting Period	Counting Site	Volume Sampled (Liters)	Number of Counts
1971							
Jan 10	1430-2230	1	B4	1430-2230	BLO	4800	240
10-11	2230-0630	2	C4	2230-0630	BLO	4800	240
11	1500-2300	2	B3	1500-2300	GC	4800	240
11-12	2300-0700	1	B4	2300-1500	GC	9600	480
12-13	1500-2300	2	B3	1500-1000	GC	11000	550
13-14	1500-2300	1	B3	1500-0320	GC	7400	370
15	1130-1930	2	B4	1130-2300	HR	6900	345
25	1100-1900	2	C2	1100-1900	HR	4800	240
Feb 4-5	1400-2200	2	C3	1400-1000	HR	12000	600
10	1200-2000	1	C4	1200-2020	HR	5000	250
15	0930-1730	2	C3	0930-1130	BLO	4800	240
19	0830-1630	1	C2	0830-1830	TG	6000	300
25	0030-0830	2	C4	0030-0830	HR	4800	240
Mar 8	0530-1330	1	C1	0530-1330	HR	4800	240
10	0700-1500	2	C2	0700-1500	TG	4800	240
11	0430-1230	2	C3	0430-1230	HR	4800	240
12	0130-0930	1	B3	0130-1130	TG	6000	300
12-13	2030-0430	2	B3	2030-0630	TG	6000	300
13	0500-1300	1	B4	0500-1300	TG	4800	240
15	0130-0930	1	B3	0130-0930	HR	4800	240
17	0030-0830	1	A2	0030-1030	BLO	6000	300
17	0900-1700	1	C3	0900-1700	BLO	4800	240
22-23	2330-0730	2	C3	2330-0730	TG	4800	240
23	0730-1530	2	C4				
23-24	1630-0030	1	B3	1530-2330	TG	4800	240
25-26	1830-0230	2	B3	1830-0430	BLO	6000	300
26	0230-1030	1	B4	0230-1600	BLO	7800	390
26-27	1600-2400	2	B3	1600-0800	BLO	9600	480

and M intervals for monthly and annual concentrations are presented in Figure 19.

As during ground seeded events, NS2 concentrations in general have medians, ranges, and variabilities which are as large as or larger than those for seeded periods. NS1 concentrations are significantly smaller (at the 1 percent level) than the NS2 and S concentrations at all stations and for all months.

The largest concentration of ice nuclei found during ground seeding operations was 60 nuclei per liter at Hyde Park on February 16, 1969. During the two years that airborne seeding was used, no station had concentrations larger than 25 nuclei per liter, with the following exception. On February 19, 1971 counts as large as 45 nuclei per liter were recorded, and on January 10, 1970 counts as high as 1500 were recorded. These high counts did not occur at a low elevation station, but at a relatively high station--Tony Grove. Figures 20 and 21 show the 10 minute average counts on these two days. On both days increases were sudden and, to a lesser degree, decreases were sudden. There can be little doubt that these increases are due to seeding activities.

Although Tony Grove is located in a bowl shaped valley, it is not thought that the high concentrations of nuclei represent the pooling or trapping of ice nuclei.

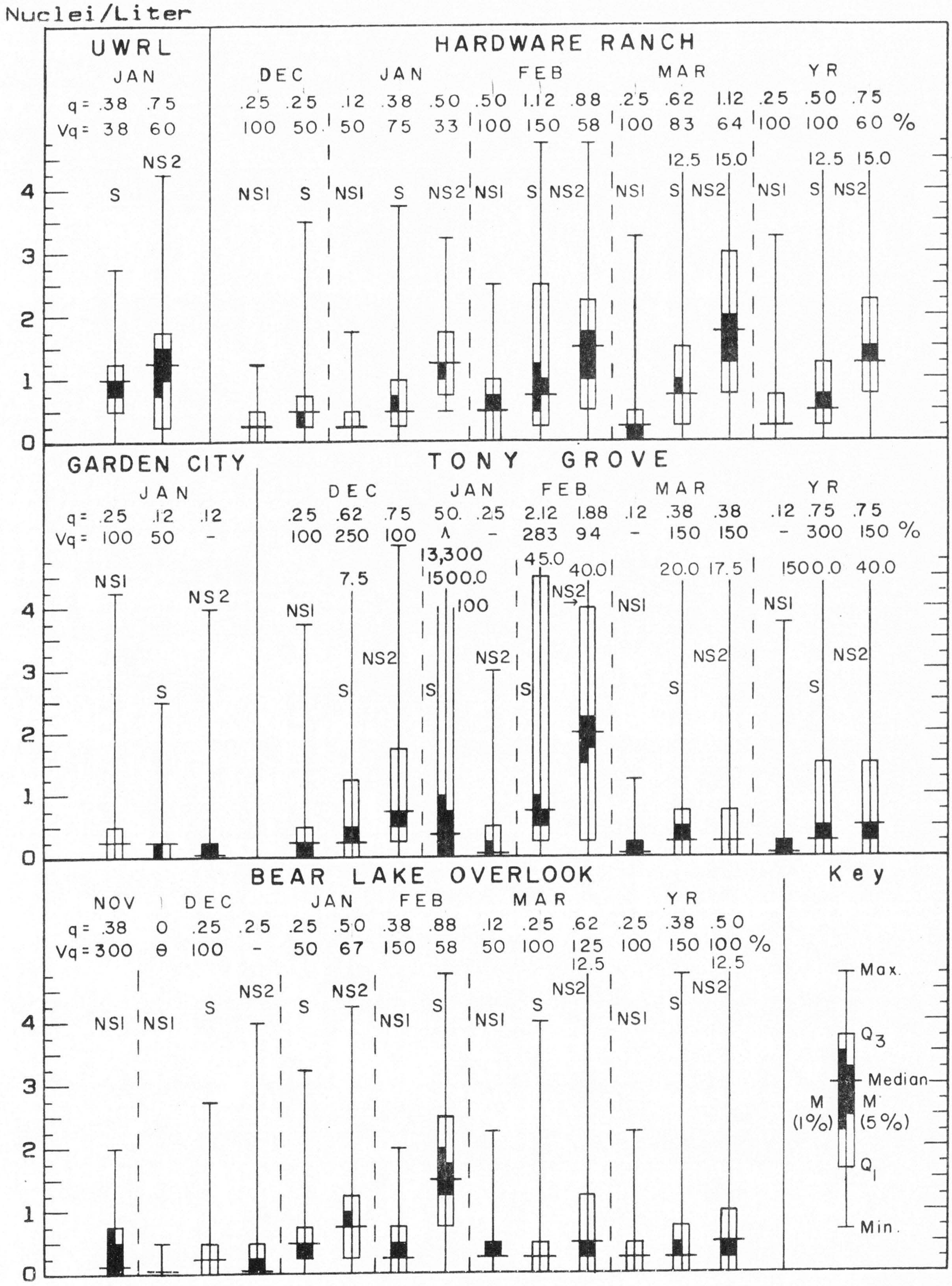


Figure 19. Ice nuclei distributions during seeded (S), nonseeded first (NS1), and nonseeded second (NS2) halves of experimental events.

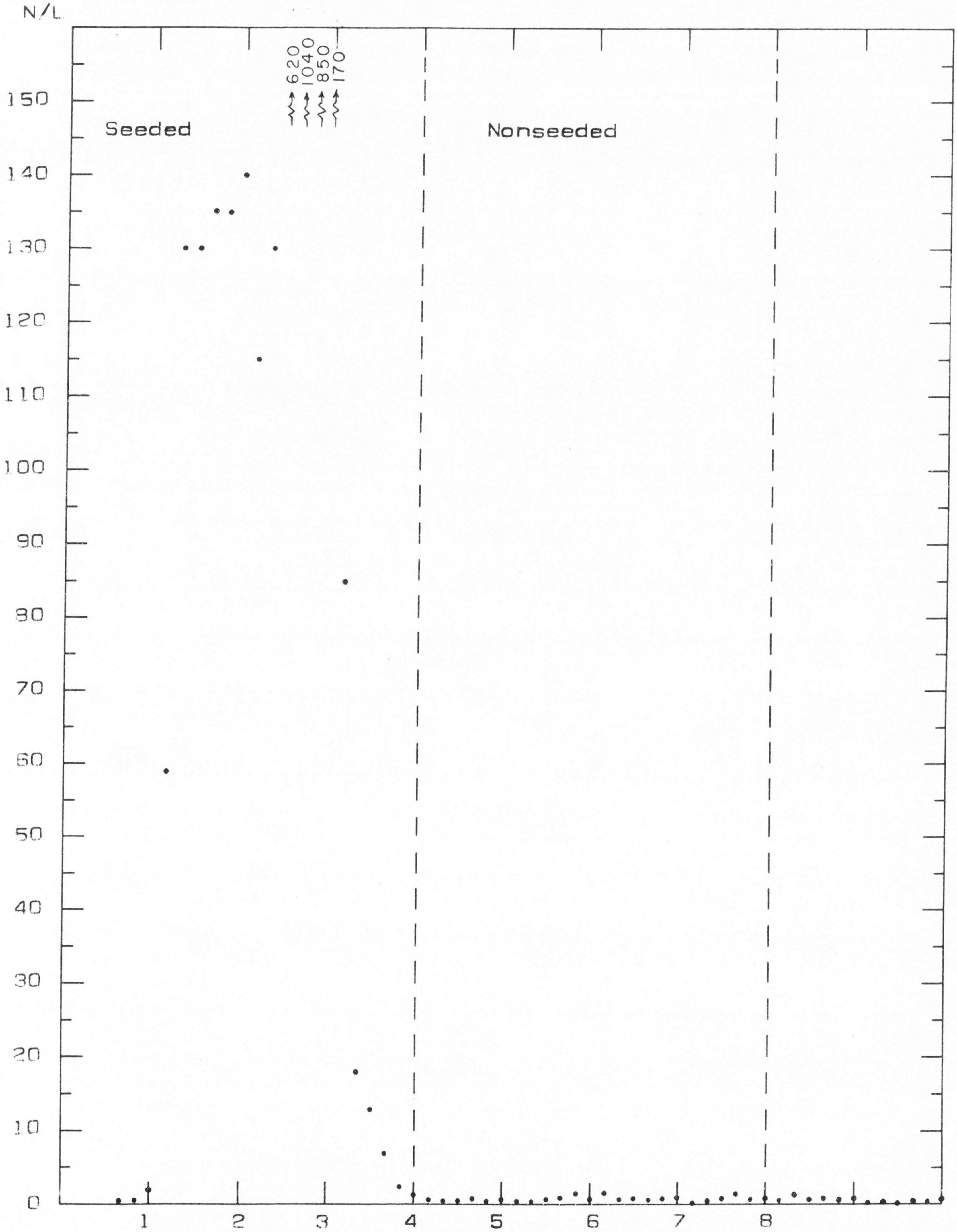


Figure 20. Ice nuclei concentrations measured at Tony Grove during an experimental event beginning at 1100, January 10, 1970.

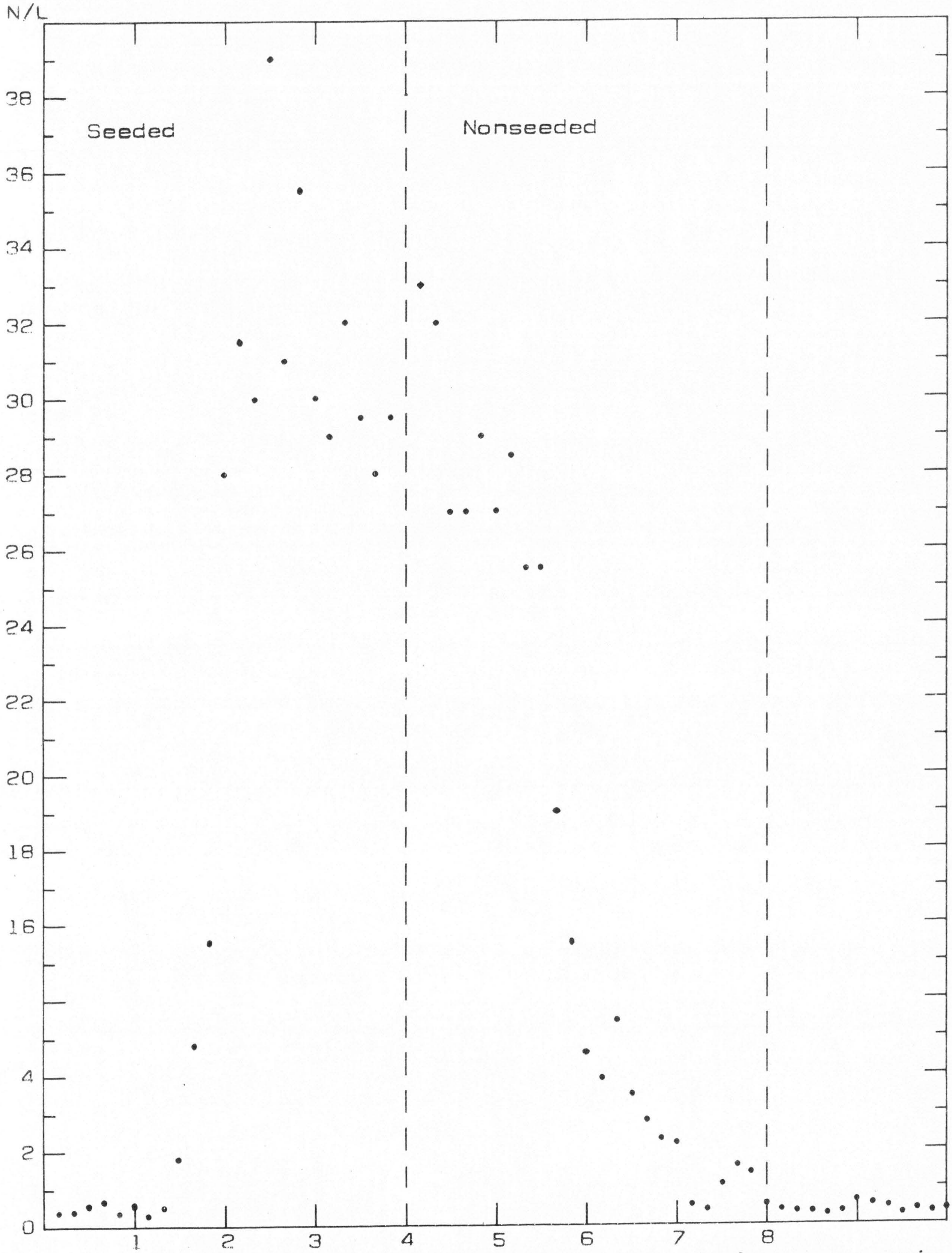


Figure 21. Ice Nuclei concentrations during an experimental event beginning at 0830 MST, February 19, 1971.

Rawinsonde data indicated that the ice nuclei were being released into a layer of stable air. Hewson (1955) pointed out that under similar meteorological conditions the effluent emitted from stacks would remain in a narrow and thin plume or cloud in high concentrations with little diffusion taking place for great distances downwind of the release site. The fact that the high concentrations did not continue into the nonseeded period even though no noticeable change in meteorological conditions took place, would tend to indicate that the high counts were not due to pooling (see Figure 20).

The geographic conditions at Hardware Ranch offer the best opportunity for pooling of nuclei. This location is at a fairly low elevation in a narrow valley fed by many canyons which can act to channel the air flow and the nuclei contained in the air into the area. It is not surprising, then, that the highest concentrations during both air and ground seeded events are found for the 4 hour period following the seeded period at Hardware Ranch. Also, the average time which passes before a decrease is noticed after seeding begins is longer than for any other station. Residual counts remained in the area for longer than 19 hours on two occasions.

Even though this last statement might indicate that ice nuclei are being channeled into the Cache Valley, counts taken with the mobile counter did not indicate high concentrations in the Valley proper. This may be due to dilution once the nuclei reach the much larger Cache Valley, or it may be that the nuclei never make it to the Valley floor to be counted, since a fairly stable layer of air often persists there. It should also be pointed out that the Hardware Ranch location is well within the target area; high concentrations were never found in canyons or other locations upwind of the seeders.

Ratios of total number of ice nuclei counted during the seeded events compared to nonseeded events, as during ground seeding, indicate that seeding the first period of an experimental event results in high residual counts during the nonseeded second period. The S/NS1 ratio of 2.7 was more than double the S/NS2 ratio of 1.2.

Considering all events, the ratio of ice nuclei during the seeded period to that during the nonseeded period was 2.3:1. This indicates that ice nuclei released by aircraft frequently reach the area in which counts are being taken. It cannot be said for certain that this indicates that the ice nuclei are getting into the cloud at all times, but during nearly half of the events counting was actually carried out within the clouds. Ratios were not noticeably different for events occurring in and out of the clouds.

A study was made of the elapsed time from the release of artificial ice nuclei until increases, and subsequent decreases, in ice nuclei concentrations were noticed at the counting site. Some of these measurements may also be influenced by fluctuations in natural ice nuclei concentrations. Of 39 events with sufficient data for this study, only 10 cases showed reductions to near background levels by the end of the 2 hour buffer period included in the seeded period. The average length of time required to reach background levels after the completion of seeding was found to be 4.6 hours for those events seeded by aircraft. A 6 hour buffer period would be more useful. Only 7 cases showed the need for a longer period. It was also found that an average of 2 hours passed before increases were noticed in the target area.

On 8 occasions out of 47, no increase could be detected in the target area. This does not necessarily indicate that the nuclei did not reach the target area. There are several instances where no increase in ice nuclei would be expected. The most obvious would be the case where a stable layer existed between the counting location and the point of release. Another explanation is that the nuclei were released in the cloud and were used before reaching the counting location.

Table 6 lists the tracks which were used during airborne seeding operations. Table 7 lists the factors used to determine which track was to be used during a seeding event. The number of samples available for each track was not large enough to determine whether any significant re-

Table 6. Coordinates, Headings, Distances, and Minimum Flight Altitudes for all Seeding Track Designations.[a]

Seeding Track	Start Seed From	Turn Around Point	Length of Seeding Run (NM)	Minimum Altitude
A-1	354°/13.0	340°/39.5	27.5	12,000
A-2	337°/10.0	335°/34.0	24.5	11,000
A-3	310°/ 7.5	327°/29.5	22.0	8,000
A-4	277°/ 8.5	318°/25.0	19.5	8,000
A-5	255°/11.0	304°/22.0	17.0	9,000
B-1	348°/14.0	338°/41.5	27.5	12,000
B-2	328°/14.0	331°/40.0	26.0	11,000
B-3	310°/16.0	323°/39.5	24.0	11,000
B-4	296°/19.5	315°/39.5	22.0	10,000
B-5	287°/23.0	308°/40.0	20.0	10,000
C-1	347°/16.0	339°/43.0	27.0	12,000
C-2	334°/20.0	333°/45.0	25.0	11,000
C-3	323°/24.5	328°/47.0	22.5	11,000
C-4	317°/30.0	324°/50.0	20.0	10,000
C-5	312°/35.5	320°/52.5	18.0	10,000

[a] All tracks are on headings of 153°/333° magnetic. All positions are from OGDEN VORTAC.

Table 7. Seeding Track Designations for Various Combinations of Wind Speed and Direction.

Wind Direction at Seeding Altitude	Wind Speed at Seeding Altitude (knots) 0-11	11-21	21-31	31-42	42-52
(mag) $180^{\circ} - 220^{\circ}$ (A)	A-1	A-2	A-3	A-4	A-5
(true) $197^{\circ} - 237^{\circ}$					
(mag) $220^{\circ} - 260^{\circ}$ (B)	B-1	B-2	B-3	B-4	B-5
(true) $237^{\circ} - 277^{\circ}$					
(mag) $260^{\circ} - 300^{\circ}$ (C)	C-1	C-2	C-3	C-4	C-5
(true) $277^{\circ} - 317^{\circ}$					

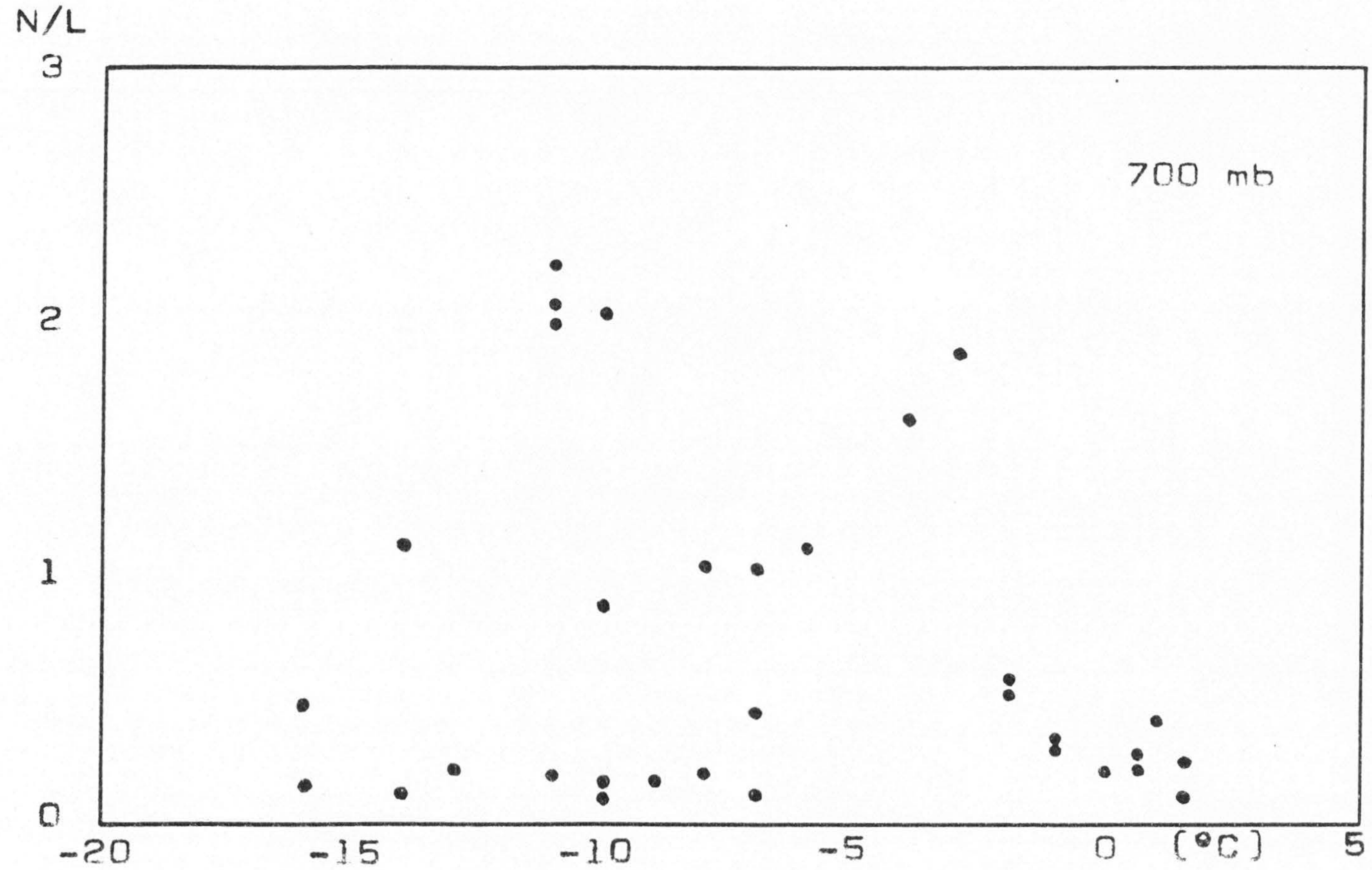
lationship existed between ice nuclei concentration and the track used. Also, no relationship was found between ice nuclei concentrations and elevation at which seeding occurred.

Ice Nuclei Numbers vs. Meteorological Conditions

Scattergrams were prepared to show relations (or lack of relations) which may have existed between ice nuclei concentrations and various meteorological parameters during background, seeded, and nonseeded (buffer) periods. Considered were winds (both direction and speed) and temperatures at the 500, 700, and 850 mb levels, cloud top and cloud base temperature, and surface pressure. If close relationships were found, a statistical test would be used to test the relationship. However, most relationships were so poor as to make it a waste of time to run statistical tests (Figure 22 is a typical plot).

Cloud top temperatures

The only scattergram that did not look like a plot of random numbers is that between cloud top temperature and ice nuclei concentration for Tony Grove and Bear Lake Overlook (Figure 23). The relation between cloud top temperature and ice nuclei concentration may be explained as follows. The chamber of the NCAR ice nuclei counter was kept at -20 C. Therefore, regardless of the atmospheric



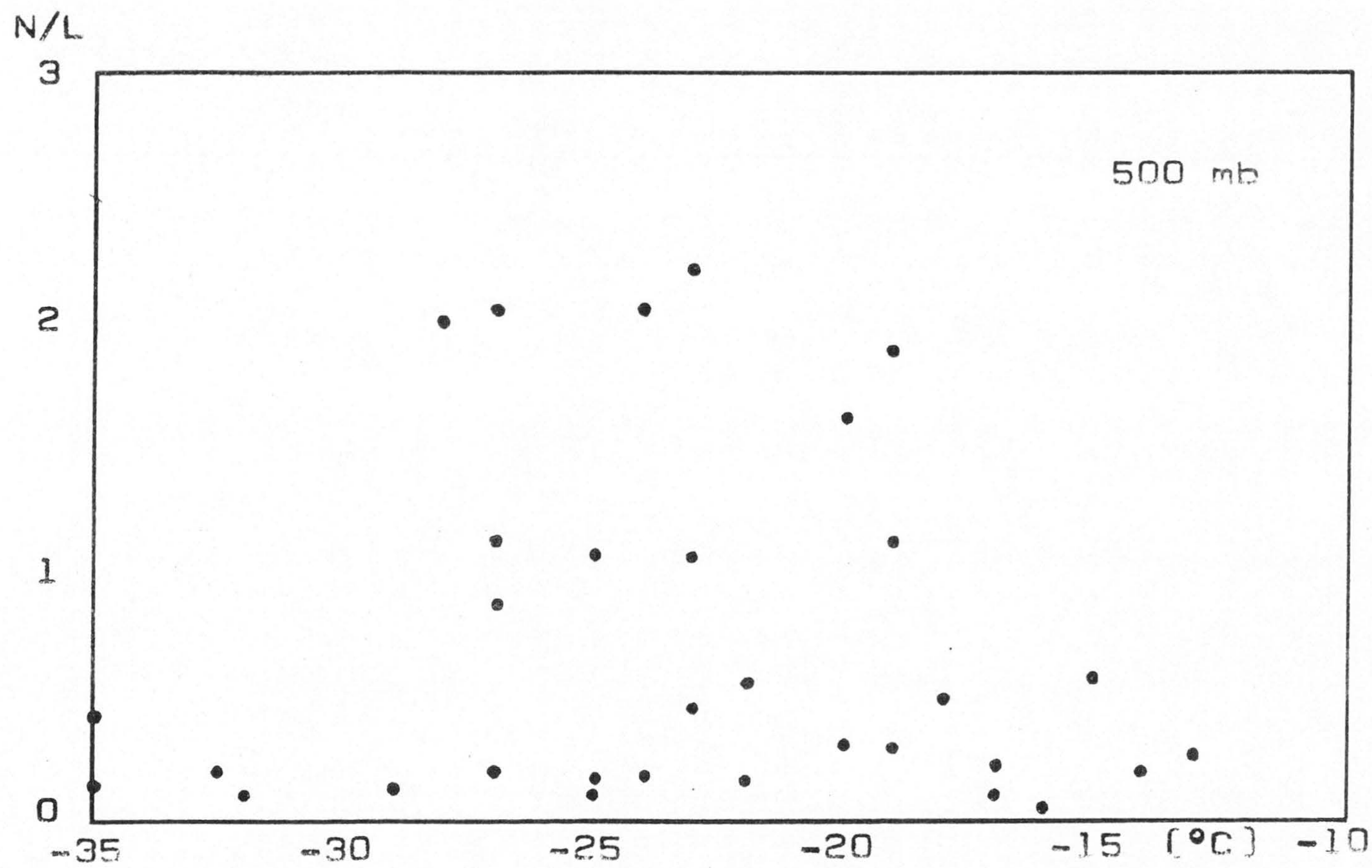


Figure 22. Ice nuclei concentration vs. 500 mb and 700 mb temperatures during seeded events in 1970 and 1971.

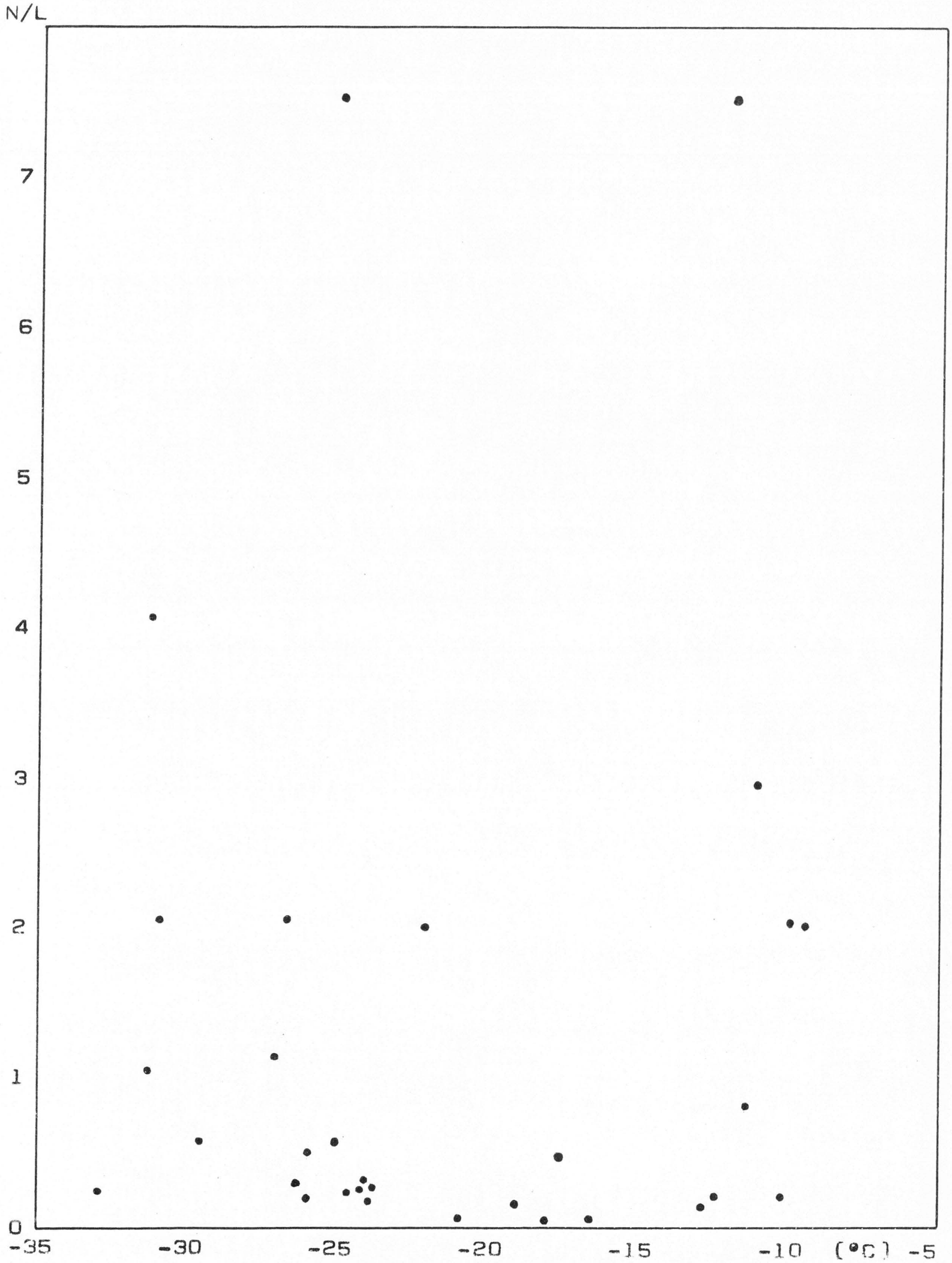


Figure 23. Ice nuclei concentration vs. cloud top temperature for data collected at Bear Lake Overlook and Tony Grove, 1969-1971.

temperature, measurements are of ice nuclei active at temperatures of -20 C and above. On days with cloud top temperatures much warmer than -20 C, counts would be expected to be high since all nuclei (both artificial and natural) active at temperatures lower than the cloud top temperature will not act as nuclei but will remain in the air mass and would be available to be counted. At cloud top temperatures near -20 C, few nuclei would be expected since they would have been used naturally and, hence, would not be available to be counted (except for those that did not get into the cloud). At temperatures near or below -30 C large numbers of nuclei would again be expected since numerous natural ice nuclei are active at this temperature and an excess is likely, especially with the addition of artificial nuclei. These relations should exist whether or not seeding is being performed and may account for fluctuations in natural ice nuclei during precipitation weather.

Wind

Figure 24 is representative of the scattergrams resulting from plotting ice nuclei concentrations against wind directions. There appears to be little relationship between wind direction and nuclei numbers, but this is largely due to the fact that the scattergram does not relate each count to other meteorological conditions at the time the measurement was taken. If this were possible, it

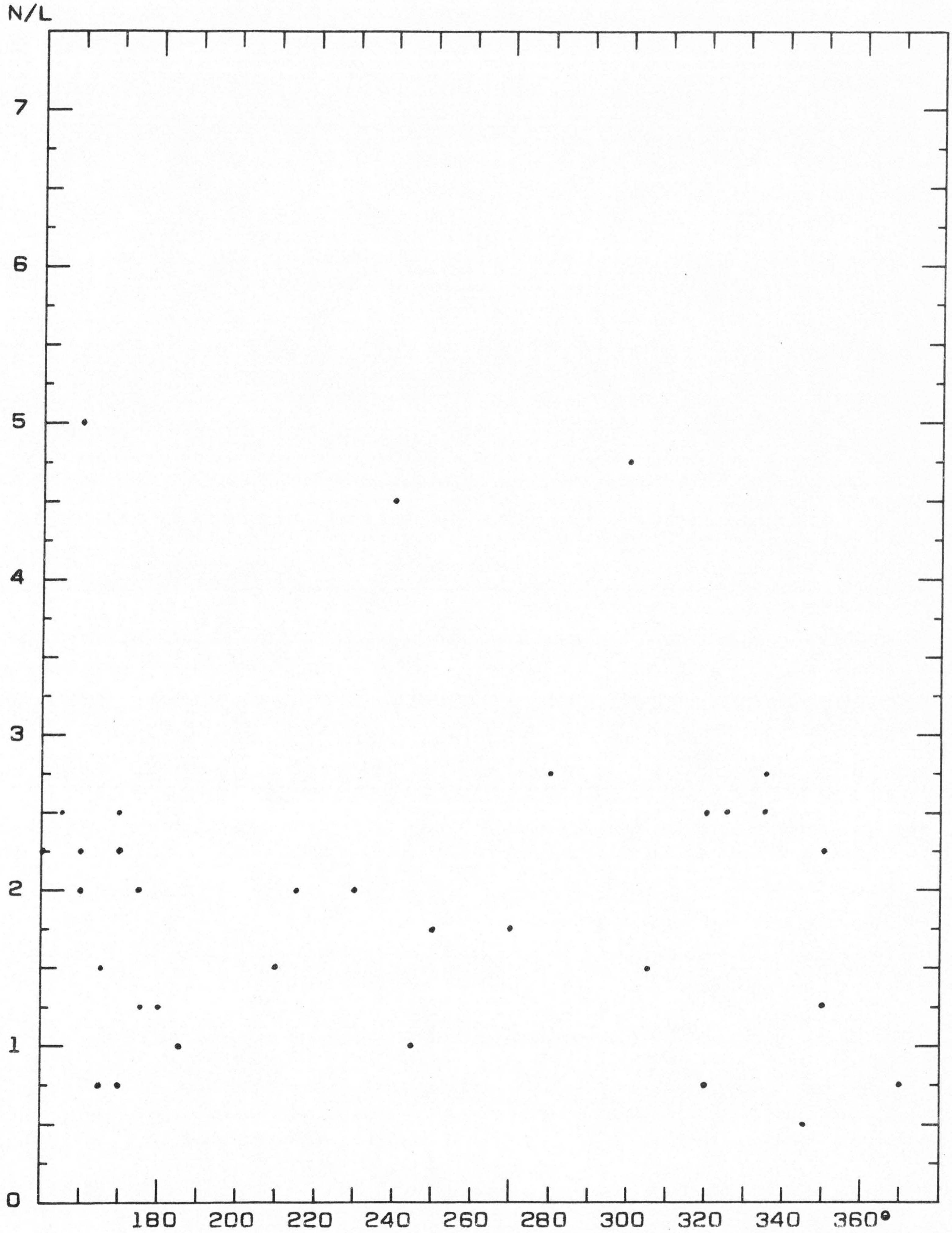


Figure 24. Ice nuclei concentration vs. wind direction at the 850 mb level during non-experimental periods, 1970.

would be seen that most concentrations above 3 nuclei per liter during background periods could be traced to the Salt Lake City area as their source.

On several occasions when the area remained under the influence of a high pressure system for several days, visual pollution from the smelters, and the Salt Lake City area in general, would extend northward for over 50 miles along the base of the Wasatch Mountains. On such occasions this pollution could find its way into the Cache Valley through passes to the south, west or north so that even with a surface wind from the north, the actual source of the nuclei during periods when the counts were high could be the Salt Lake City area. The fact that winds were predominantly from the south and southwest the first year, and from the southeast and west the following 2 years, may be the major cause of the differences in ice nuclei concentrations found during these periods.

Stability

The importance of stability to ice nuclei concentrations has already been brought out for the Salt Lake City area. Stability was also shown to be at least partially responsible for large concentrations of ice nuclei found during seeding operations. The importance of stability to the concentration of ice nuclei can be best illustrated by looking at the meteorological conditions on days with high, and days with low counts.

Figure 25 depicts the meteorological conditions on December 8, 1968. The surface map shows the area to be under the influence of a high pressure cell to the southeast of Utah. The area had been under the influence of pressure as high as 1040 mb since December 3rd. The Salt Lake rawinsondes show a very stable condition existing both in the morning and evening. Under such conditions ice nuclei concentrations would be expected to be large, and, as Figure 26 shows, high concentrations were general throughout the Cache Valley.

The large NPW concentrations found at both Hardware Ranch and Bear Lake Overlook occurred during periods of prolonged high pressure with stable conditions persisting for at least 4 days.

Ice nuclei concentrations were very low throughout the Cache Valley on February 26, 1969 as shown in Figure 27. As Figure 28 shows, these low concentrations occurred following a frontal passage on the previous day, and absolute instability existed at the time measurements were being taken.

Absolute stability persisted in the Cache Valley on some occasions when storm systems were moving through the area. Indications of this are shown by the series of observations taken at Hyde Park from December 16 to December 20, 1968 (see Figure 29). Ice nuclei concentrations at the same time on successive days increased systemati-

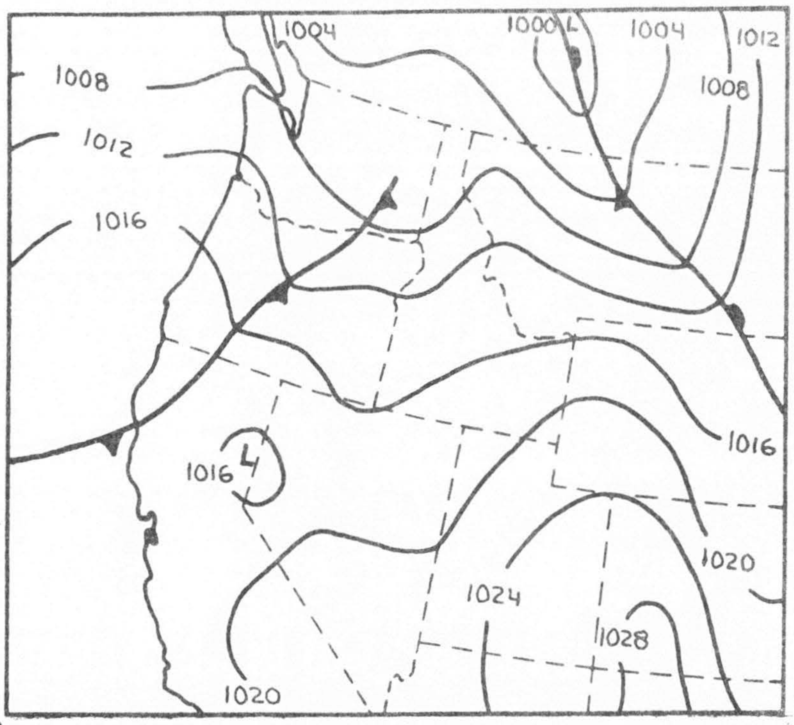
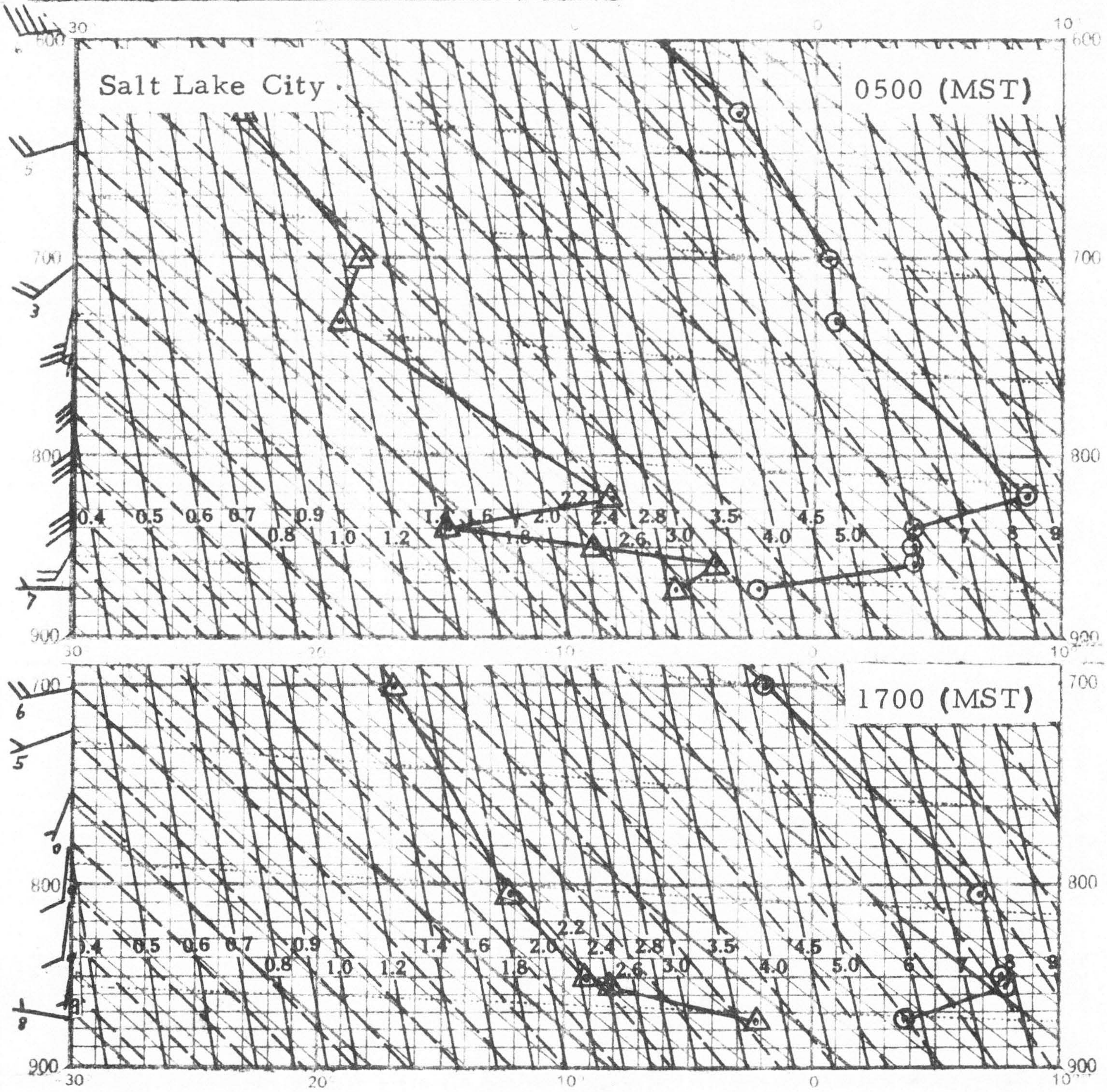


Figure 25. Surface map and pseudo-adiabatic diagram for December 8, 1968.



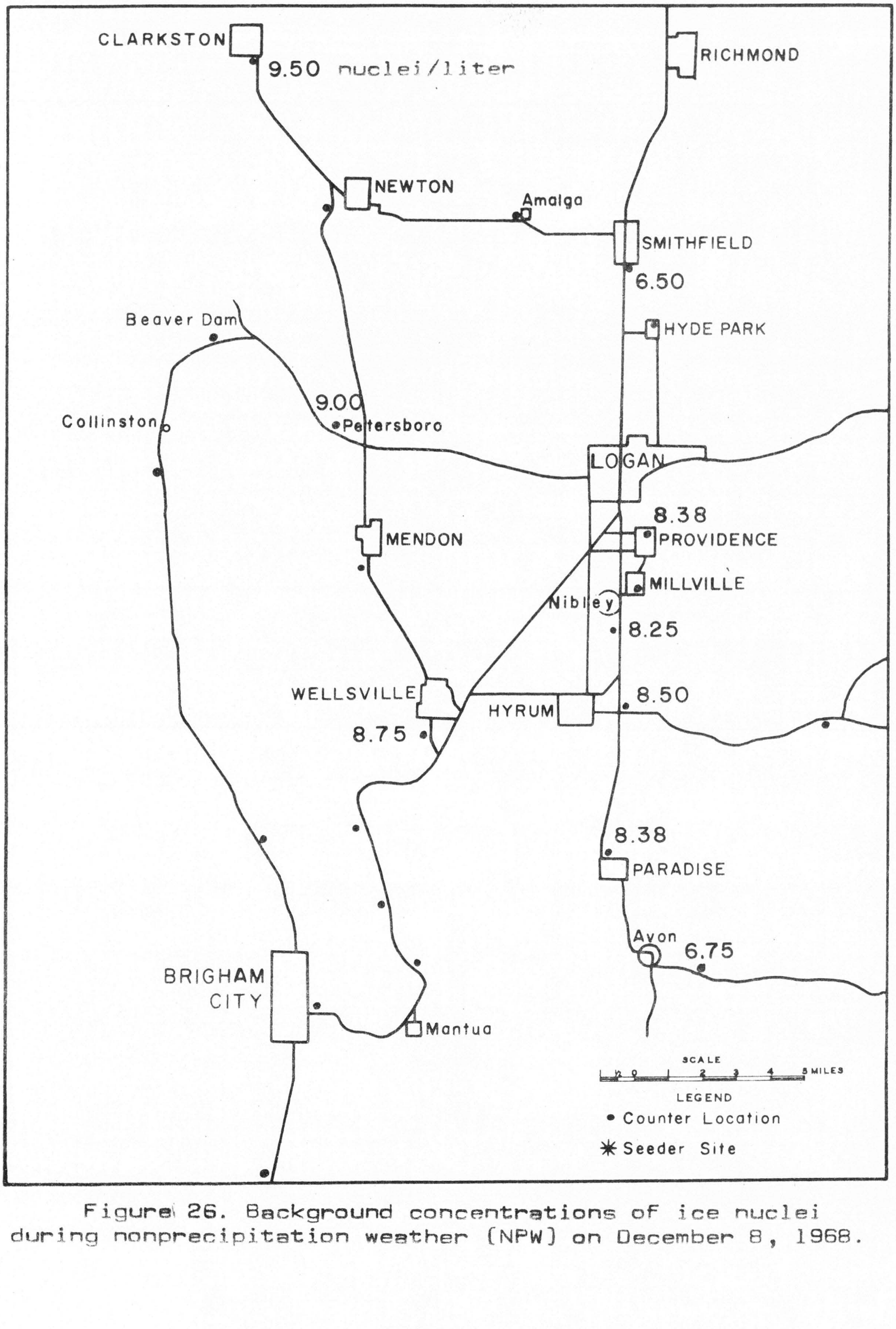


Figure 26. Background concentrations of ice nuclei during nonprecipitation weather (NPW) on December 8, 1968.

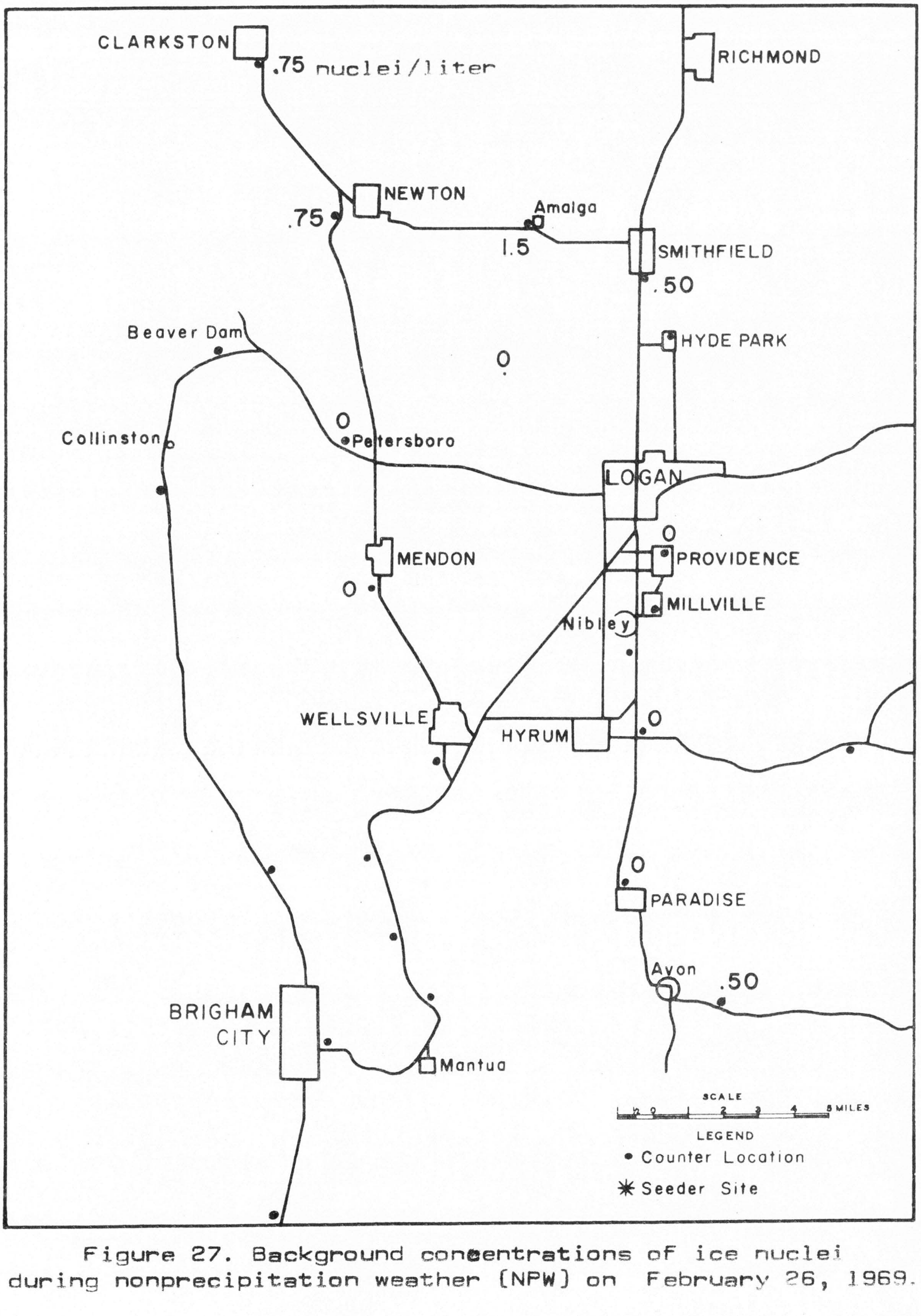


Figure 27. Background concentrations of ice nuclei during nonprecipitation weather (NPW) on February 26, 1969.

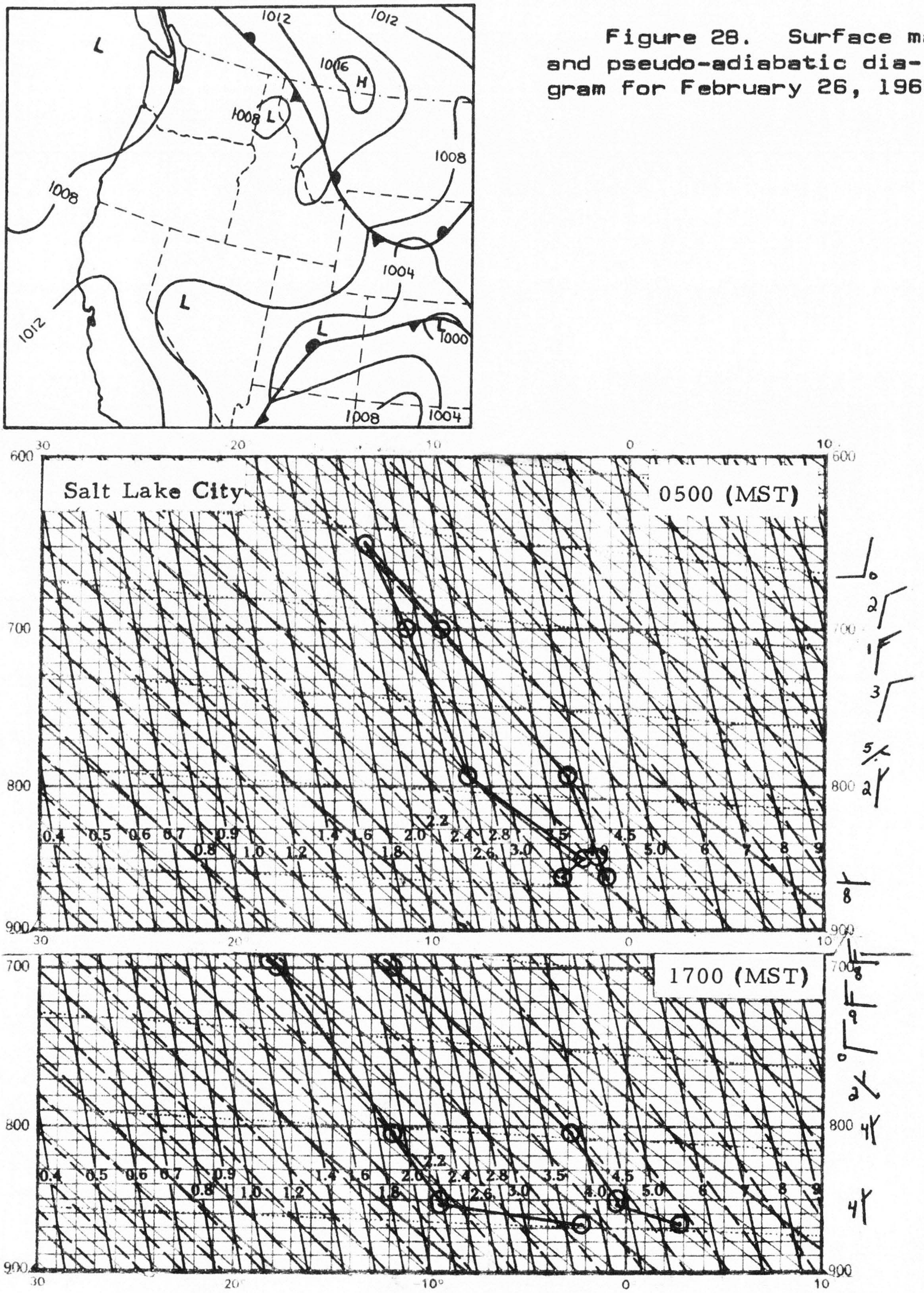


Figure 28. Surface map and pseudo-adiabatic diagram for February 26, 1969.

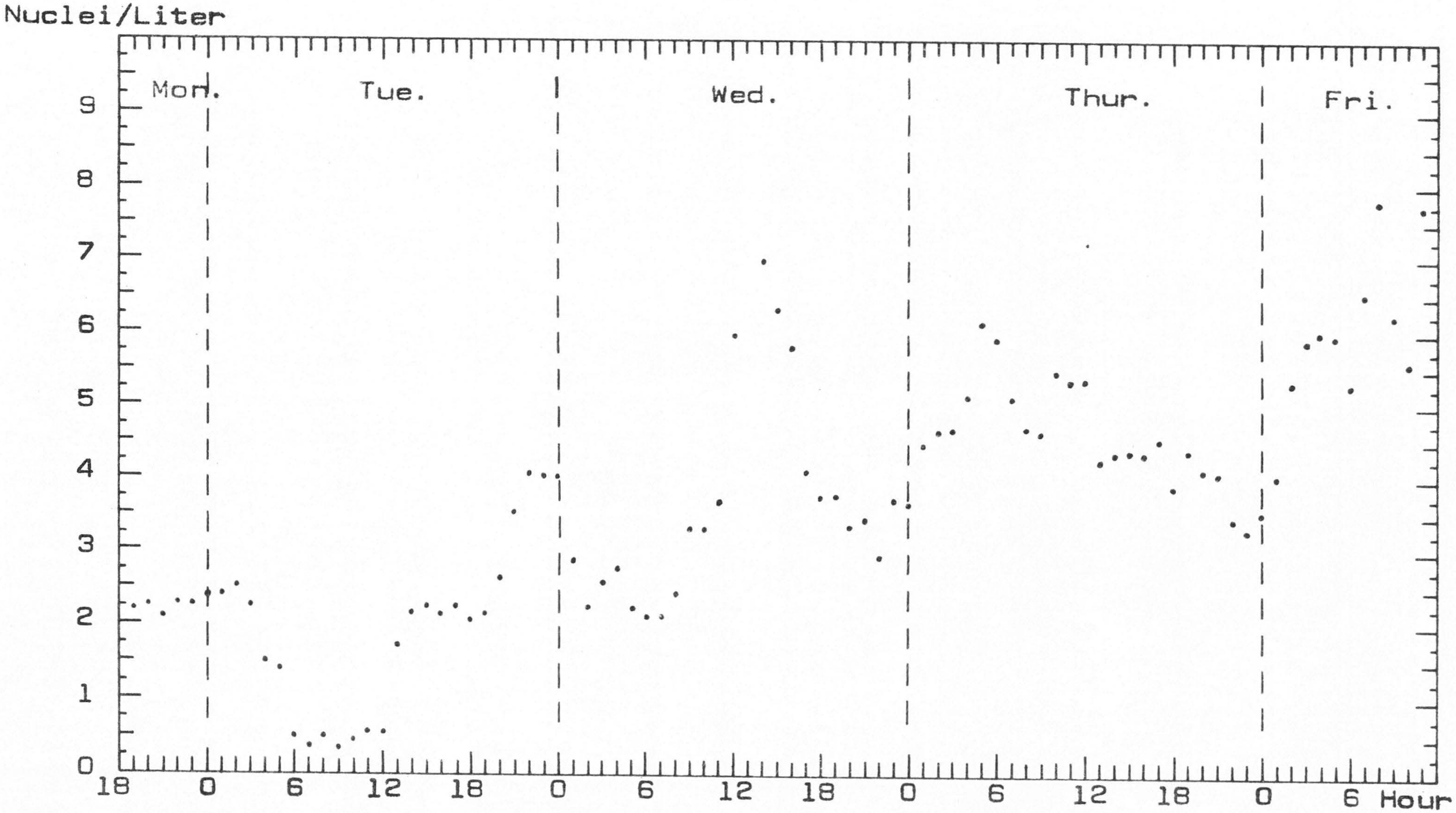


Figure 29. Variations in Ice Nuclei Concentrations for December 16 to December 20, 1968 at Hyde Park.

cally during the work week. The Friday concentrations averaged about 4 times the Monday concentrations. This accumulation occurred even though this was a week of transient weather systems, with the sea level pressure at Salt Lake City varying from 1005 to 1022 mb.

SUMMARY OF RESULTS AND CONCLUSIONS

Ice nuclei concentrations in the Wasatch Weather Modification Experimental Area were found to be as low as or lower than those reported for other areas of the world during background periods. Concentrations as large as 1750 nuclei per liter measured at -20 C were found at the surface in the Salt Lake City area, but the maximum concentration found in all other areas was 25 nuclei per liter. The majority of counts on nonseeded days on which precipitation occurred were below 0.75 nuclei per liter with the maximum reading being 5 nuclei per liter. With background ice nuclei concentrations this low, there would seem to be a great potential in the Wasatch Weather Modification Experimental Area for increasing precipitation amounts through the release of artificial ice nuclei. Data gathered suggests that the greatest potential occurs when cloud top temperatures are between -12.5 and -24.5 C.

Temporal variations were too large in the Cache Valley to allow spatial variations to be mapped. The spatial variation is not extremely large because there is no large, isolated source of ice nuclei in the Cache Valley as there is in the Salt Lake Valley. In the Salt Lake Valley spatial variations were mapped, delimiting the Garfield Smelters and the Geneva Steel Plant as major sources of ice nuclei.

When data from all 3 years were combined, there was no significant seasonal or diurnal variation at any station. A diurnal variation significant at the 5 percent level was found for April of the first year.

No indication could be found that effluent released during seeding operations was descending into the Valley in large quantities on seedable days. Effluent did descend into the Valley during clear days when the object was to trace the plume by aircraft to give an indication of occurrences during seedable periods. Obviously, what happens during clear days cannot be used to predict what happens during seedable periods.

Although there was no indication that ice nuclei were being trapped or pooled in Cache Valley, on a few occasions nuclei seemed to be channeled into the Hardware Ranch area which is located in a narrow canyon, downslope of a large drainage area. High concentrations were detected at this location for periods extending 19 hours after seeding had ceased.

The 2 hour buffer period in use during the 1969-1970 and the 1970-1971 Winter seasons was found to be insufficient. A 6 hour buffer period is recommended.

At no time were large concentrations of ice nuclei found upwind of the ground seeder during operational events.

Ratios of ice nuclei during seeded and nonseeded periods indicate that nuclei are reaching the target area when airborne seeding is used. Ratios during ground seeded events were low, although this in itself does not mean that the effluent is not getting into the clouds over the target area.

No clear relationships could be found between ice nuclei concentrations and the various meteorological conditions. All abnormally high background concentrations could be traced to the Salt Lake City area, although not all southerly winds were associated with large concentrations of ice nuclei. The best relationship established was that between cloud top temperature and ice nuclei concentrations during seeded halves of operational events. Concentrations were low when cloud top temperatures were between -12.5 and -24.5 C. Stability was also shown to be a very important factor in determining ice nuclei concentrations.

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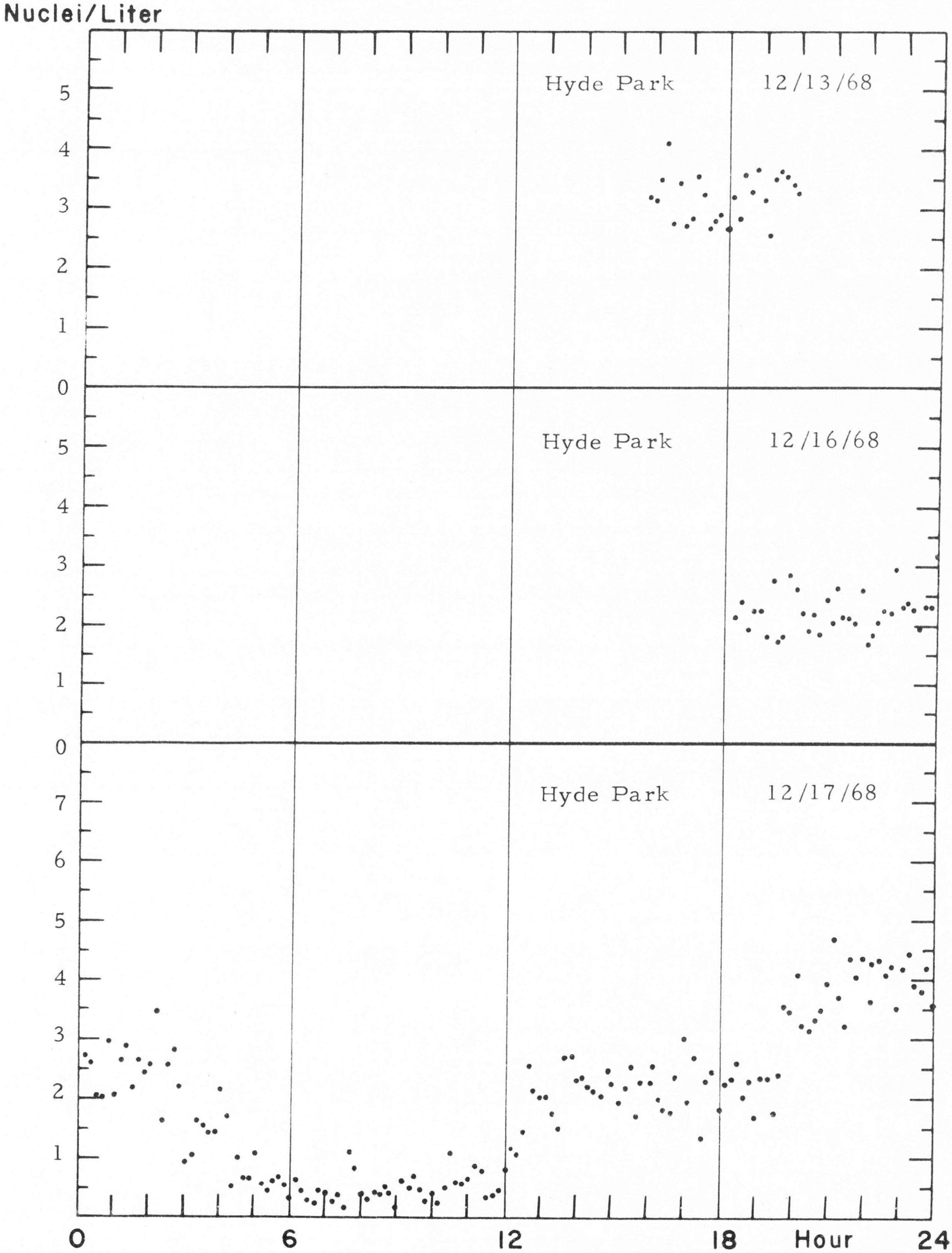
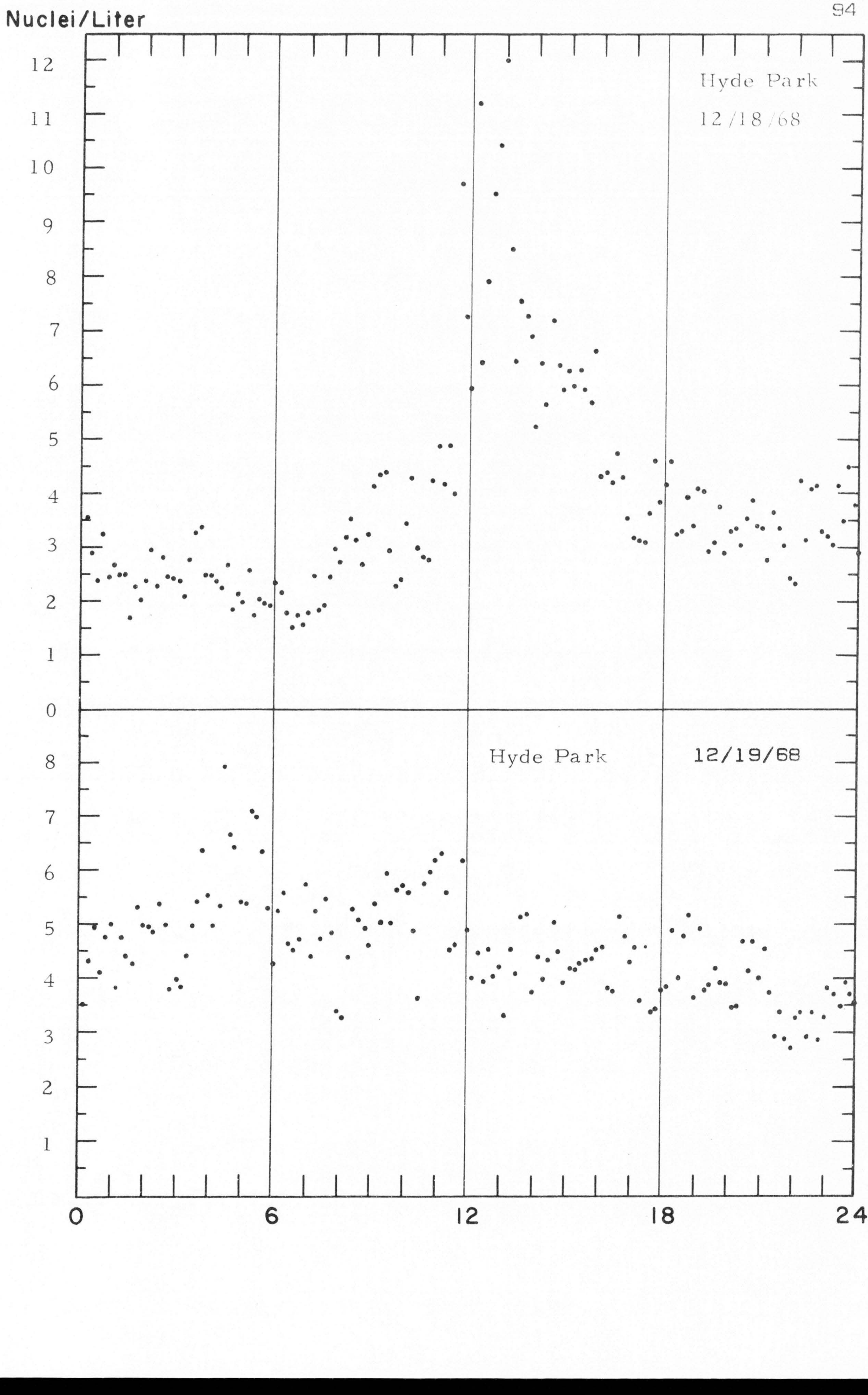
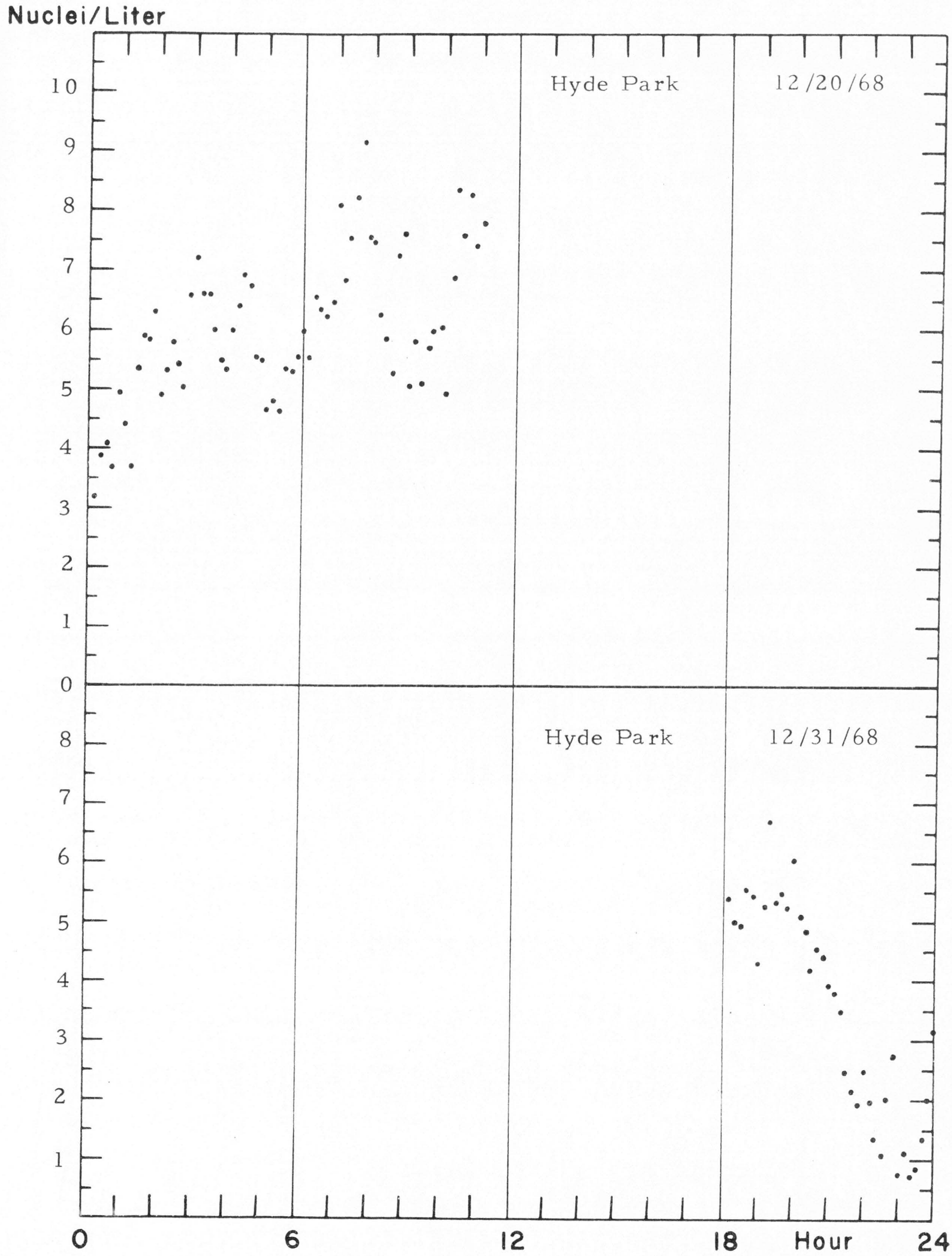
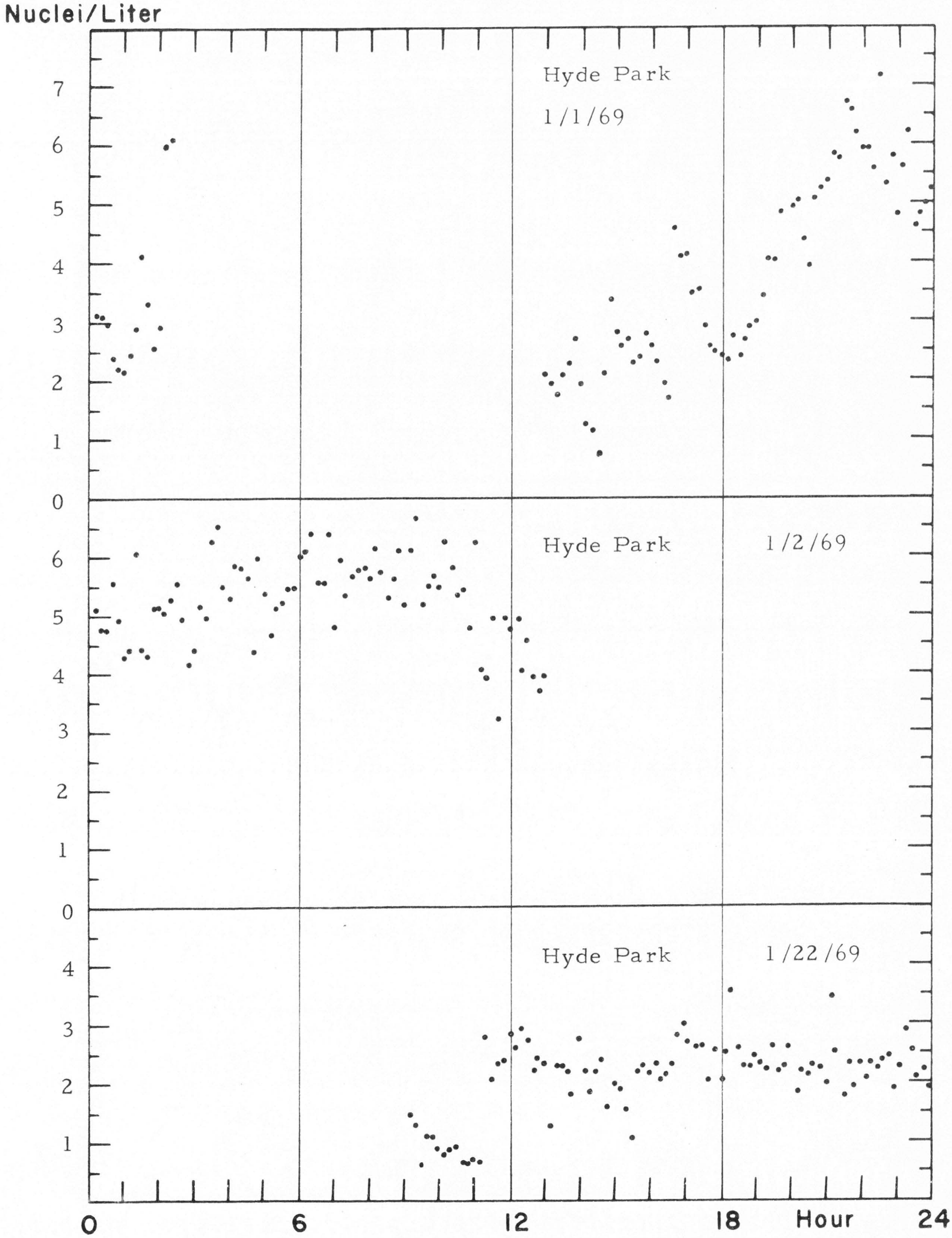
APPENDIX I

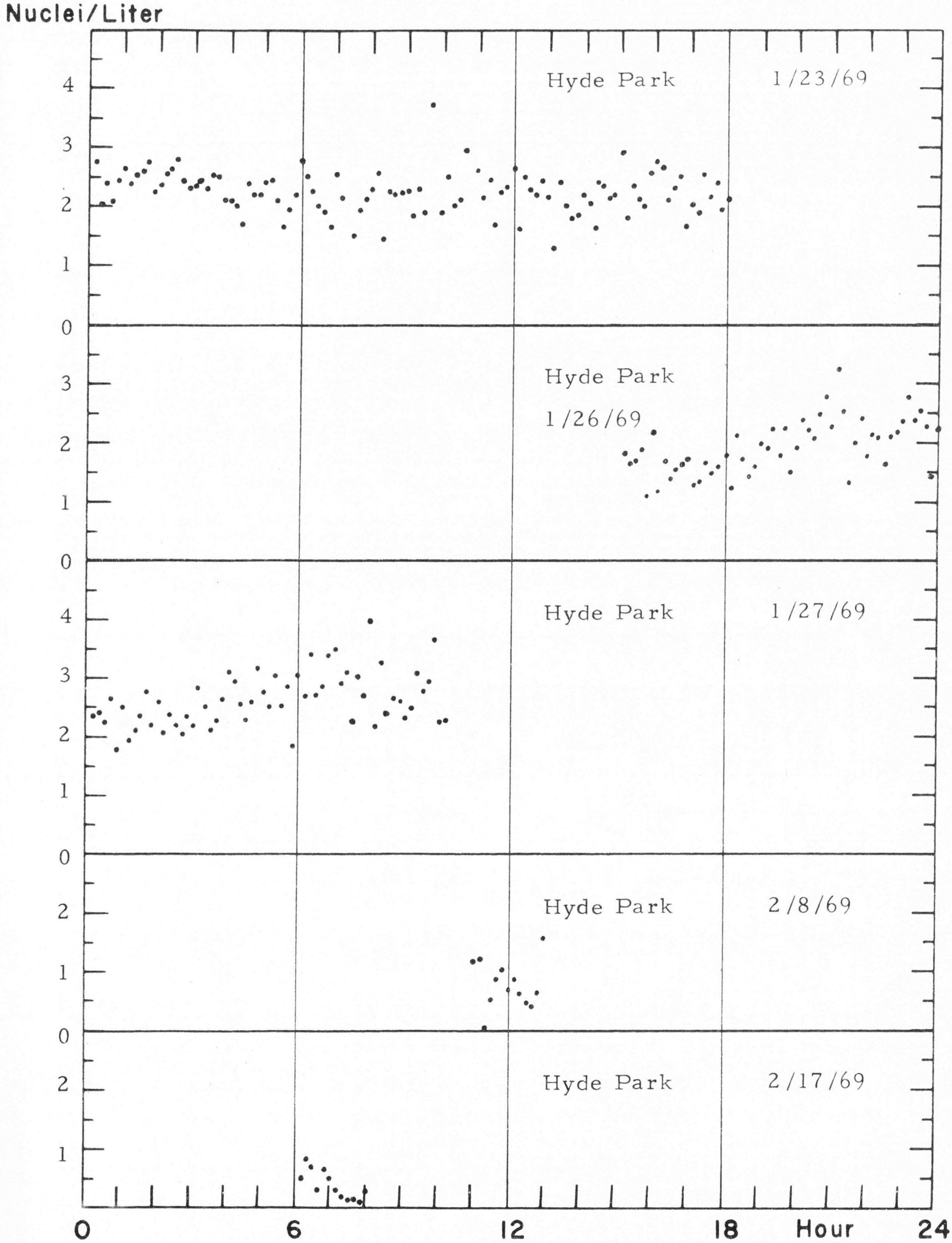
BACKGROUND COUNTS

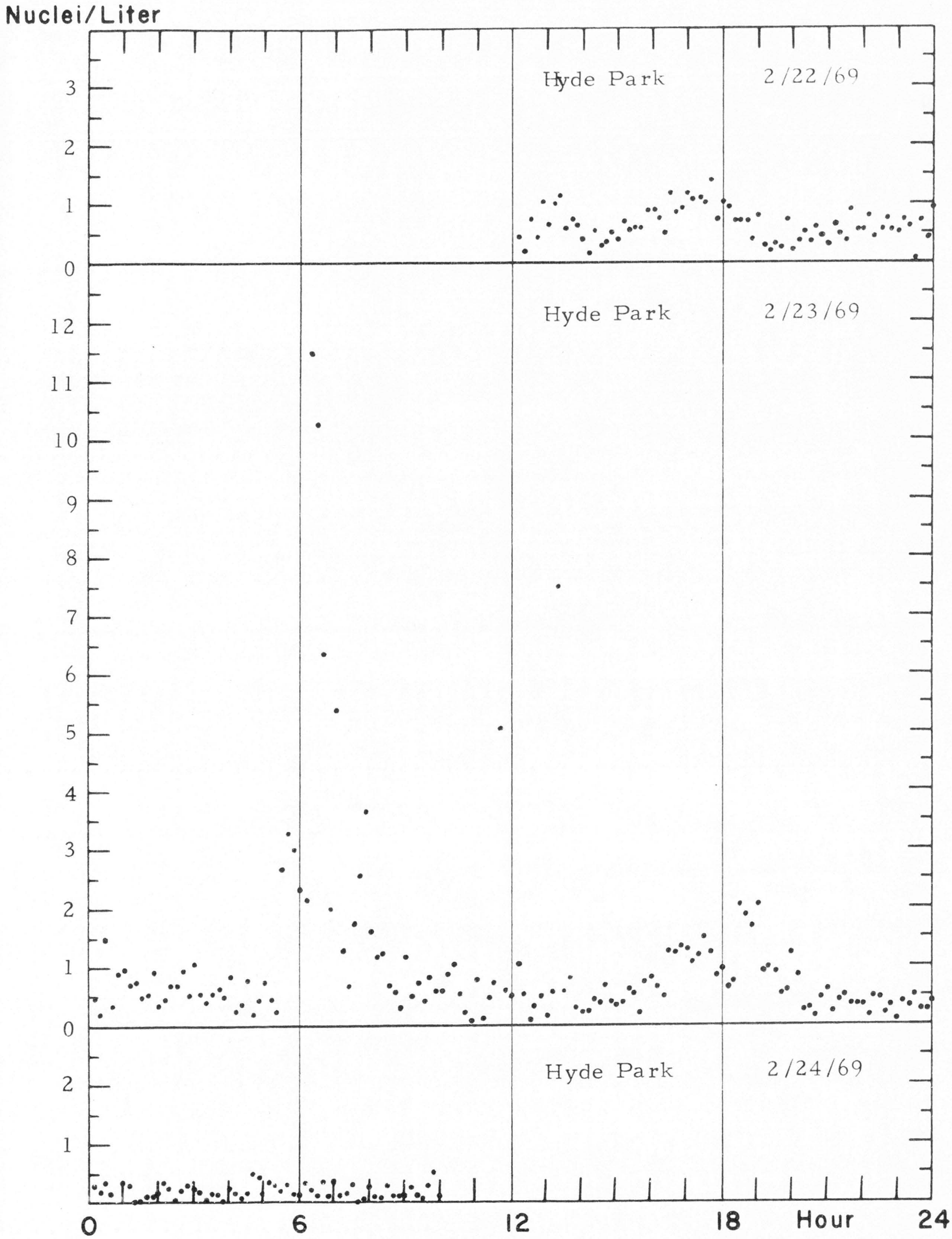

Nuclei/Liter
Hyde Park 12/13/68
Hyde Park 12/16/68
Hyde Park 12/17/68
0 1 2 3 4 5
0 1 2 3 4 5
1 2 3 4 5 6 7
0 6 12 18 Hour 24

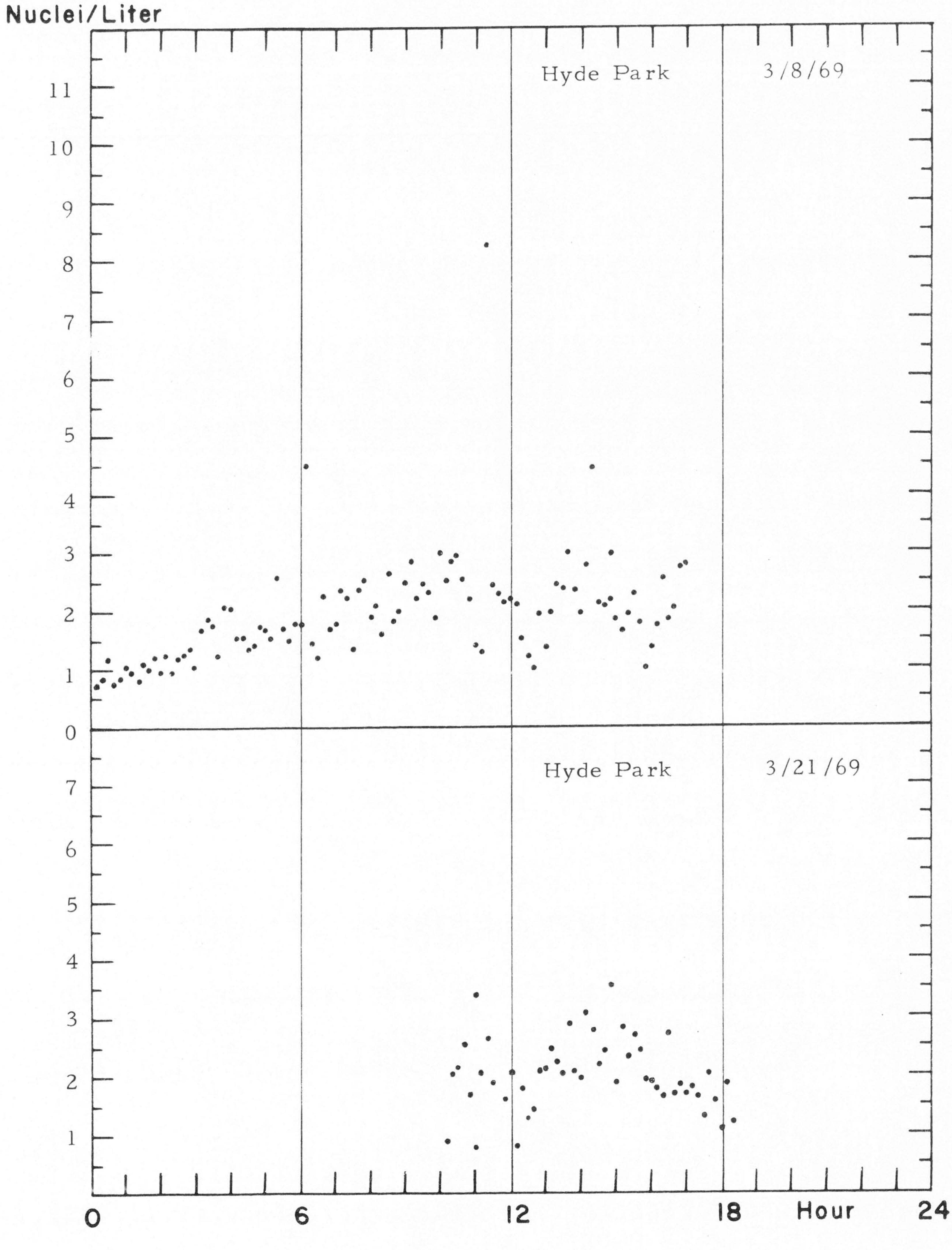

Nuclei/Liter
12
11
10
9
8
7
6
5
4
3
2
1
0
Hyde Park
12/18/68
8
7
6
5
4
3
2
1
Hyde Park
12/19/68
0
6
12
18
24

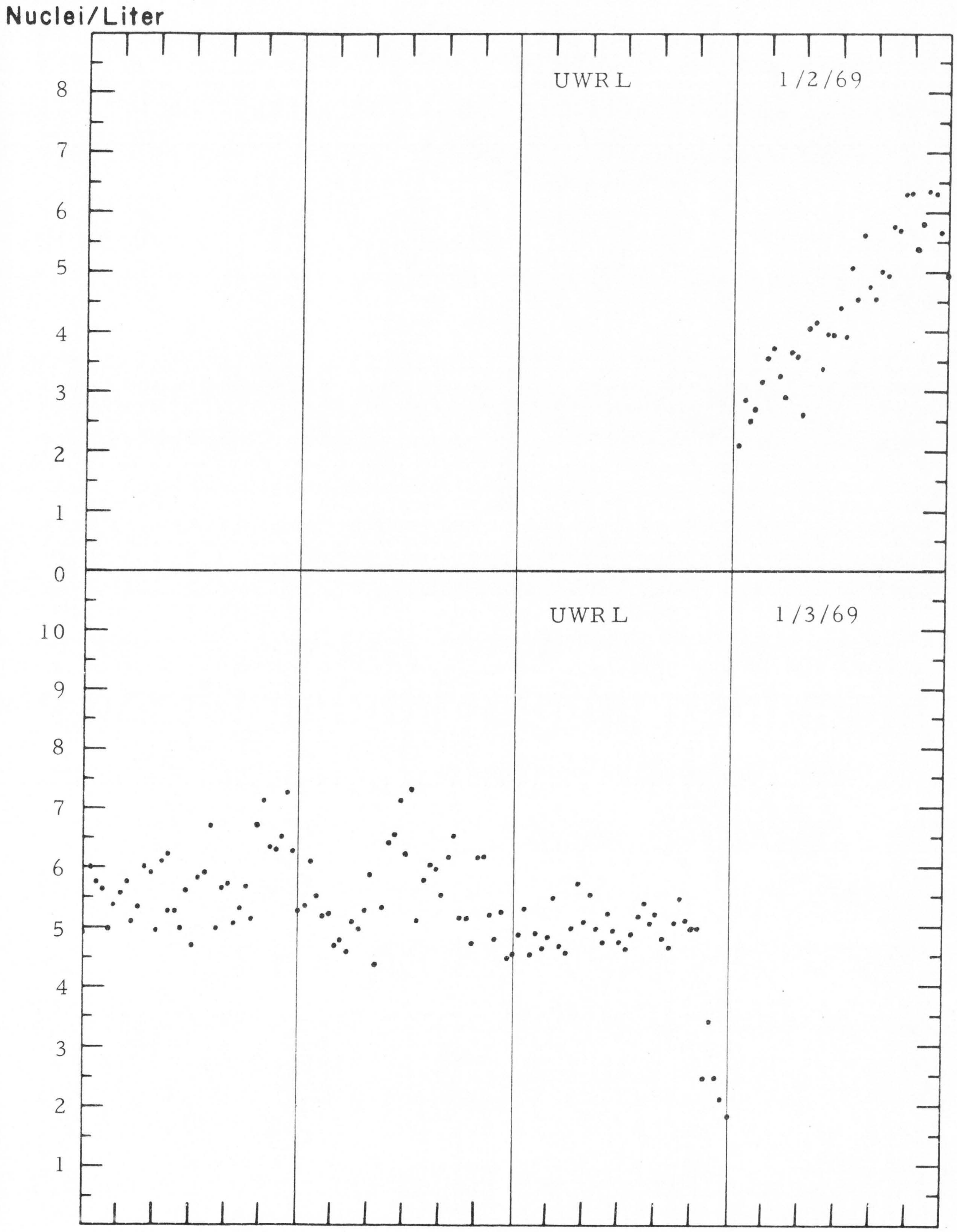

Nuclei/Liter
10
9
8
7
6
5
4
3
2
1
0
Hyde Park
12/20/68
8
7
6
5
4
3
2
1
Hyde Park
12/31/68
0
6
12
18
Hour
24

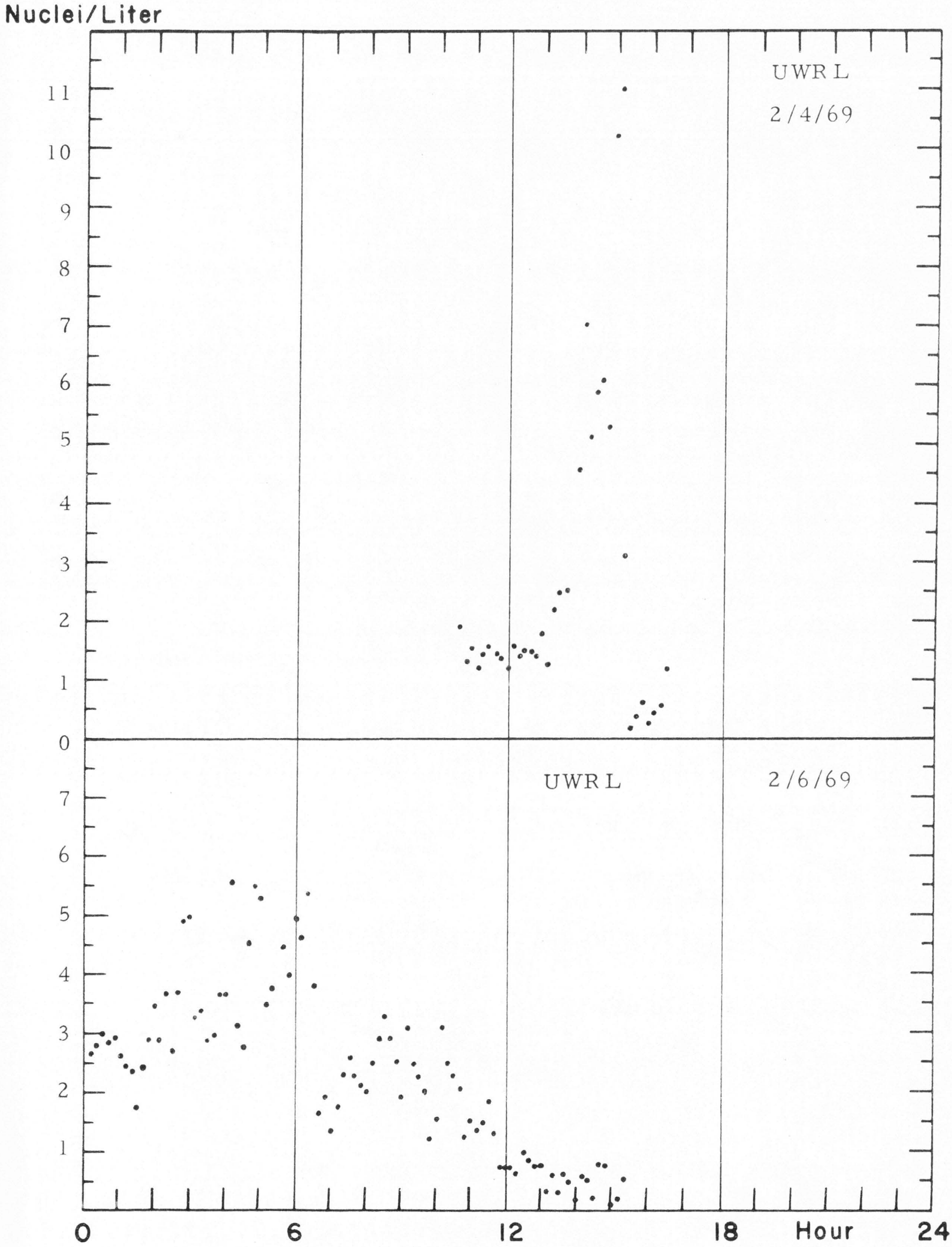

Nuclei/Liter
Hyde Park
1/1/69
Hyde Park
1/2/69
Hyde Park
1/22/69
7
6
5
4
3
2
1
0
0
6
12
18
Hour
24

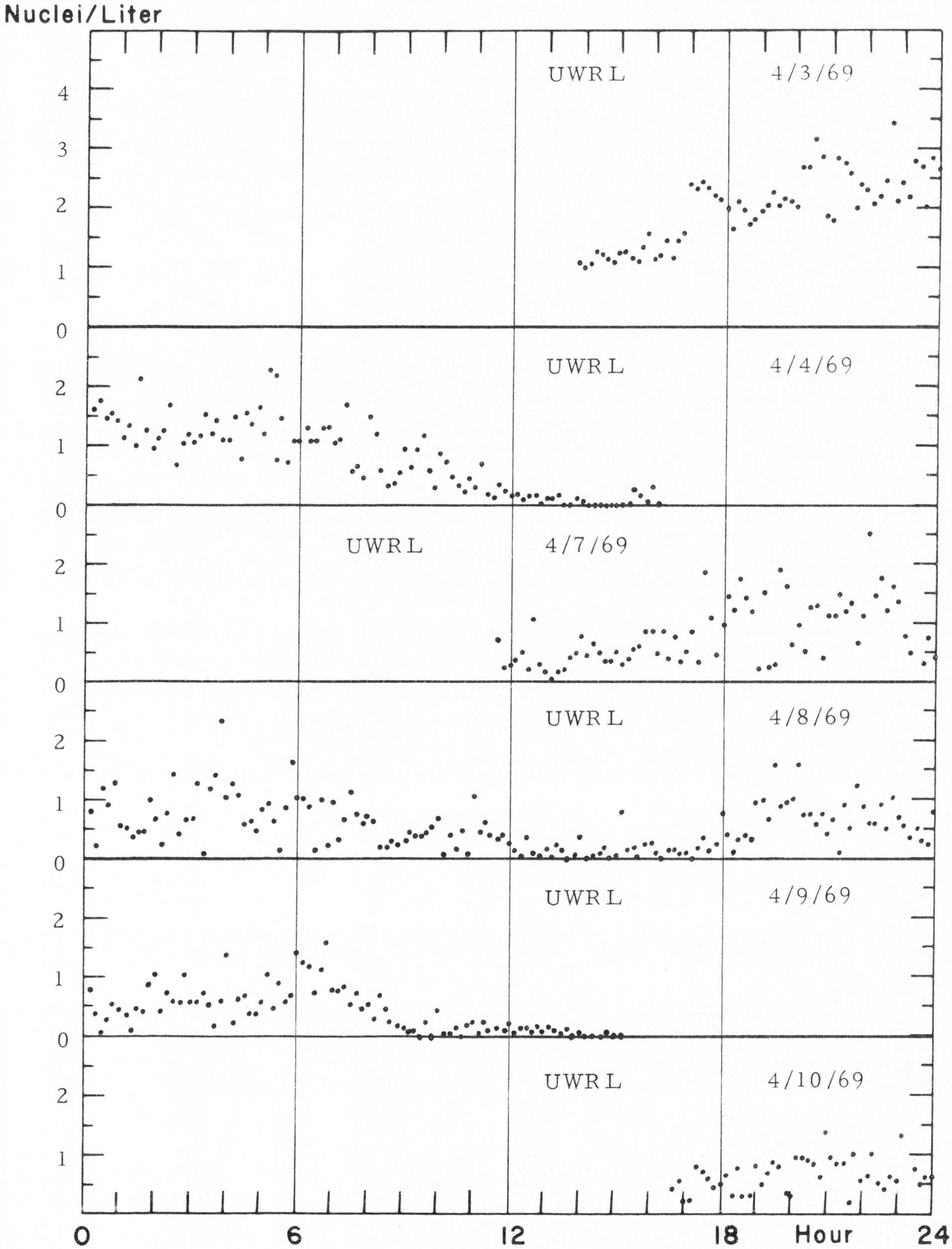

Nuclei/Liter
Hyde Park
1/23/69
Hyde Park
1/26/69
Hyde Park
1/27/69
Hyde Park
2/8/69
Hyde Park
2/17/69
0
1
2
3
4
0
6
12
18
Hour
24

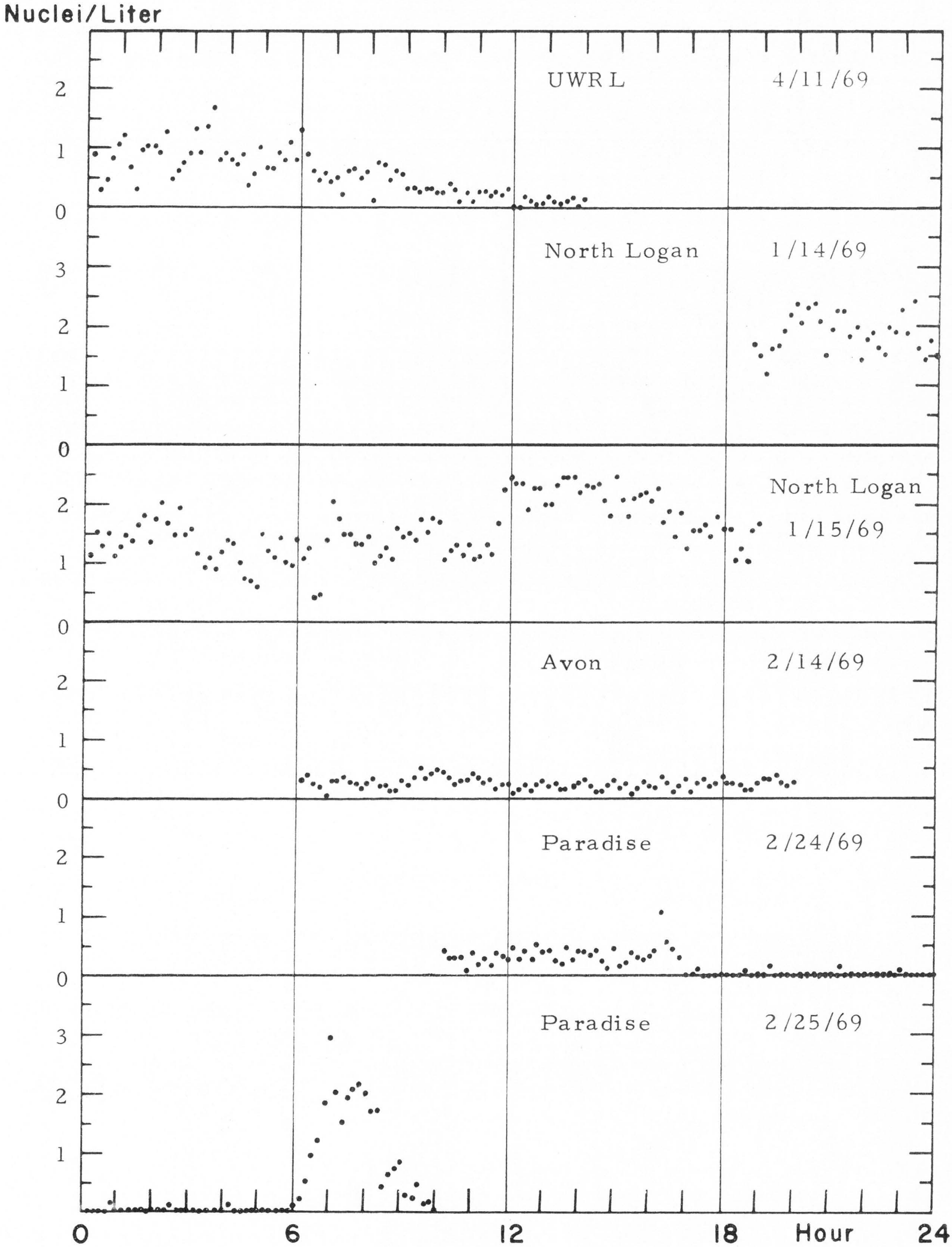

Nuclei/Liter
Hyde Park
2/22/69
Hyde Park
2/23/69
Hyde Park
2/24/69
0
1
2
3
0
1
2
3
4
5
6
7
8
9
10
11
12
0
1
2
0
6
12
18
Hour
24


Nuclei/Liter
Hyde Park
3/8/69
Hyde Park
3/21/69
0
6
12
18
Hour
24

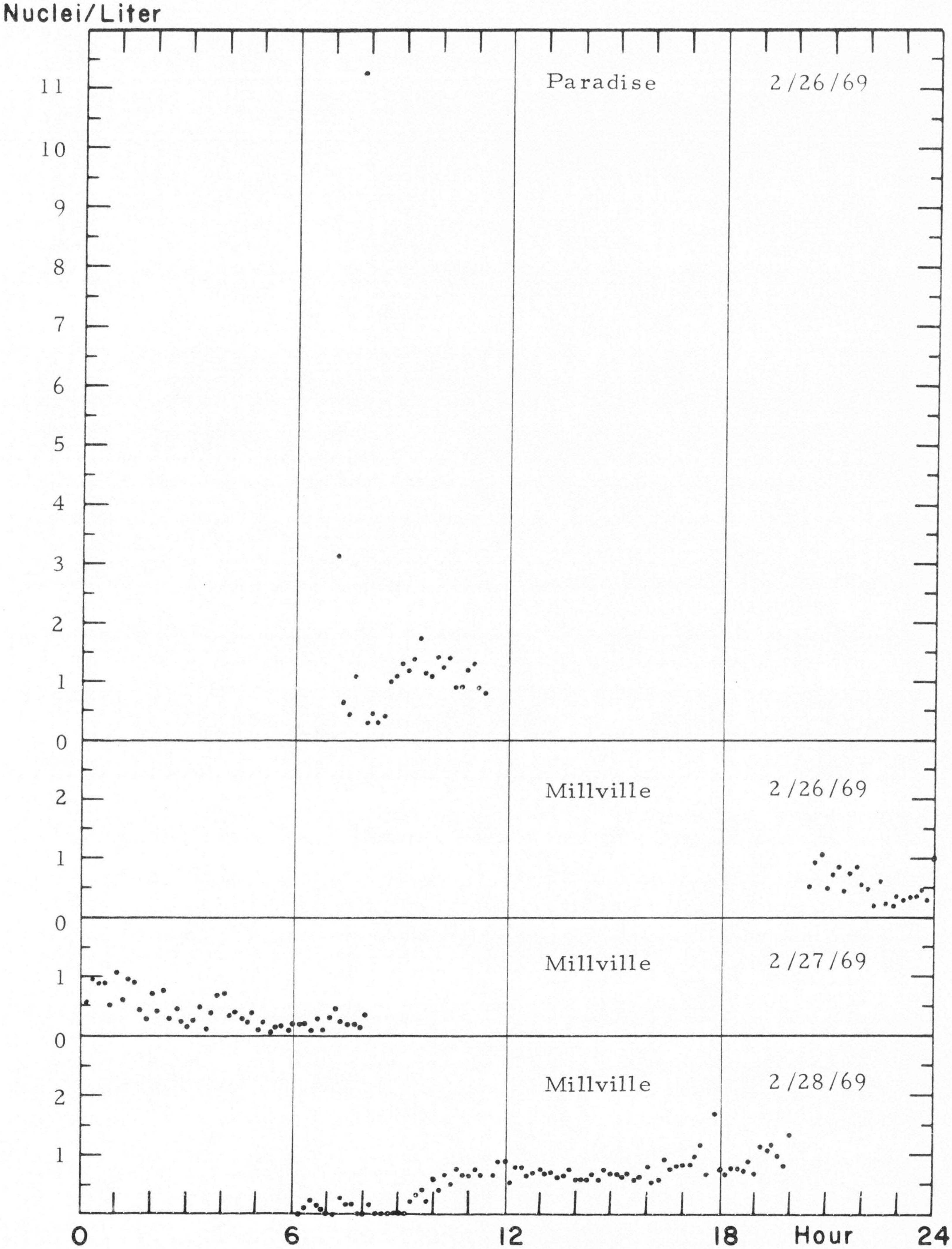

Nuclei/Liter
UWRL
1/2/69
UWRL
1/3/69
0
1
2
3
4
5
6
7
8
9
10
0
6
12
18
Hour
24


Nuclei/Liter
UWRL
2/4/69
UWRL
2/6/69
0
6
12
18
Hour
24
11
10
9
8
7
6
5
4
3
2
1
0
7
6
5
4
3
2
1


Nuclei/Liter
UWRL 4/3/69
UWRL 4/4/69
UWRL 4/7/69
UWRL 4/8/69
UWRL 4/9/69
UWRL 4/10/69
0
1
2
3
4
0
6
12
18
Hour
24



Nuclei/Liter
UWRL
4/11/69
North Logan
1/14/69
North Logan
1/15/69
Avon
2/14/69
Paradise
2/24/69
Paradise
2/25/69
0
1
2
3
0
6
12
18
Hour
24

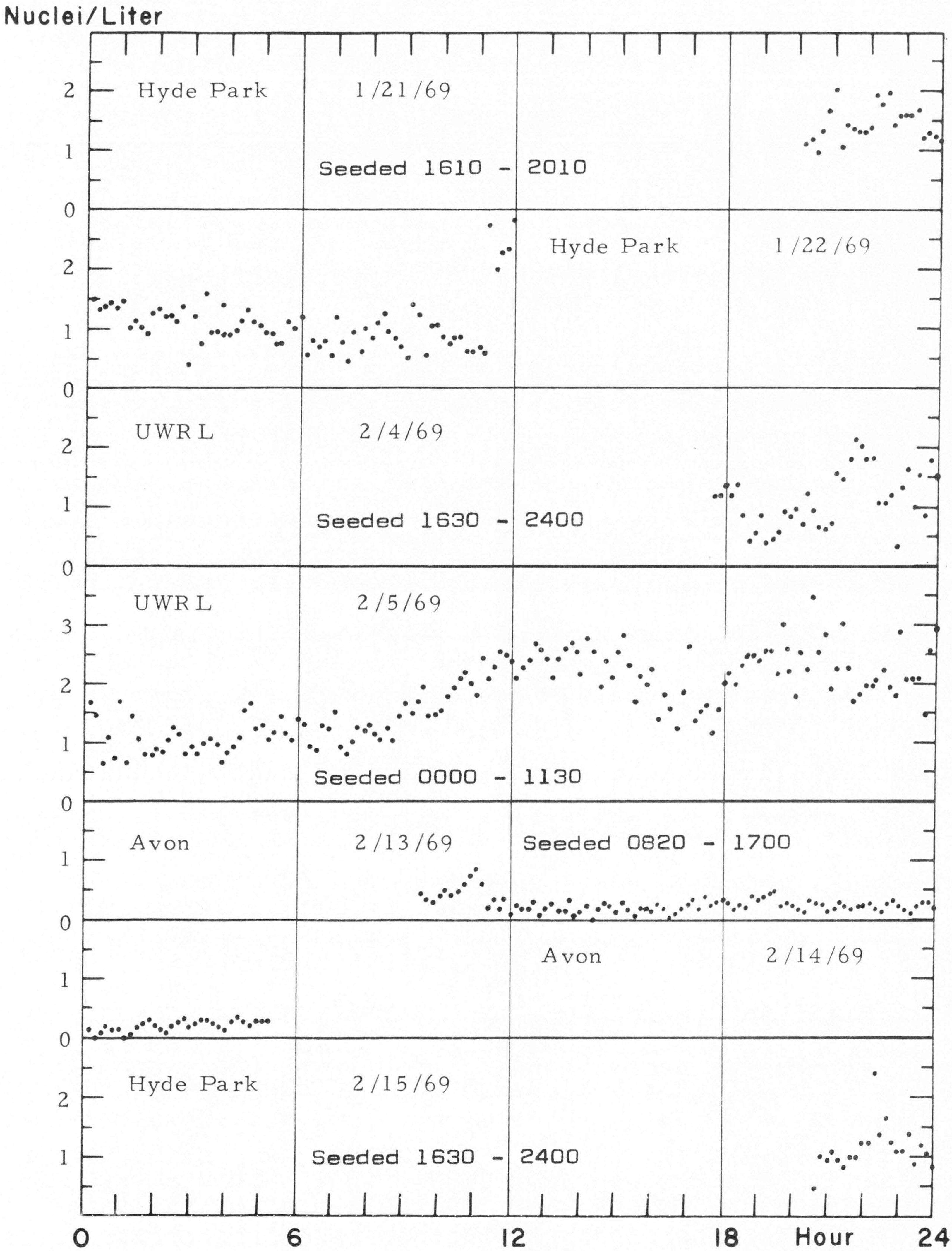


Nuclei/Liter
Paradise
2/26/69
Millville
2/26/69
Millville
2/27/69
Millville
2/28/69
0
6
12
18
Hour
24

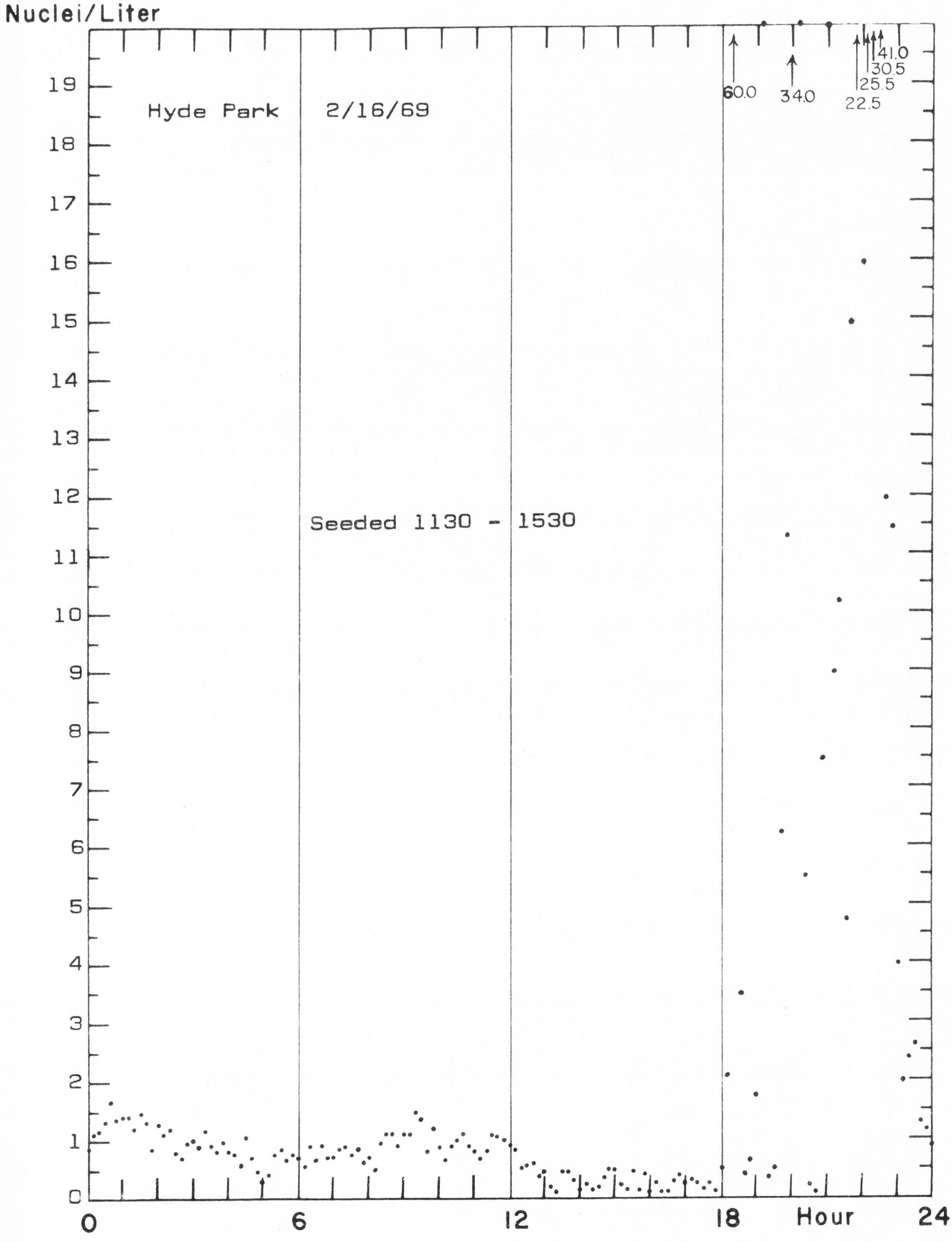
APPENDIX II

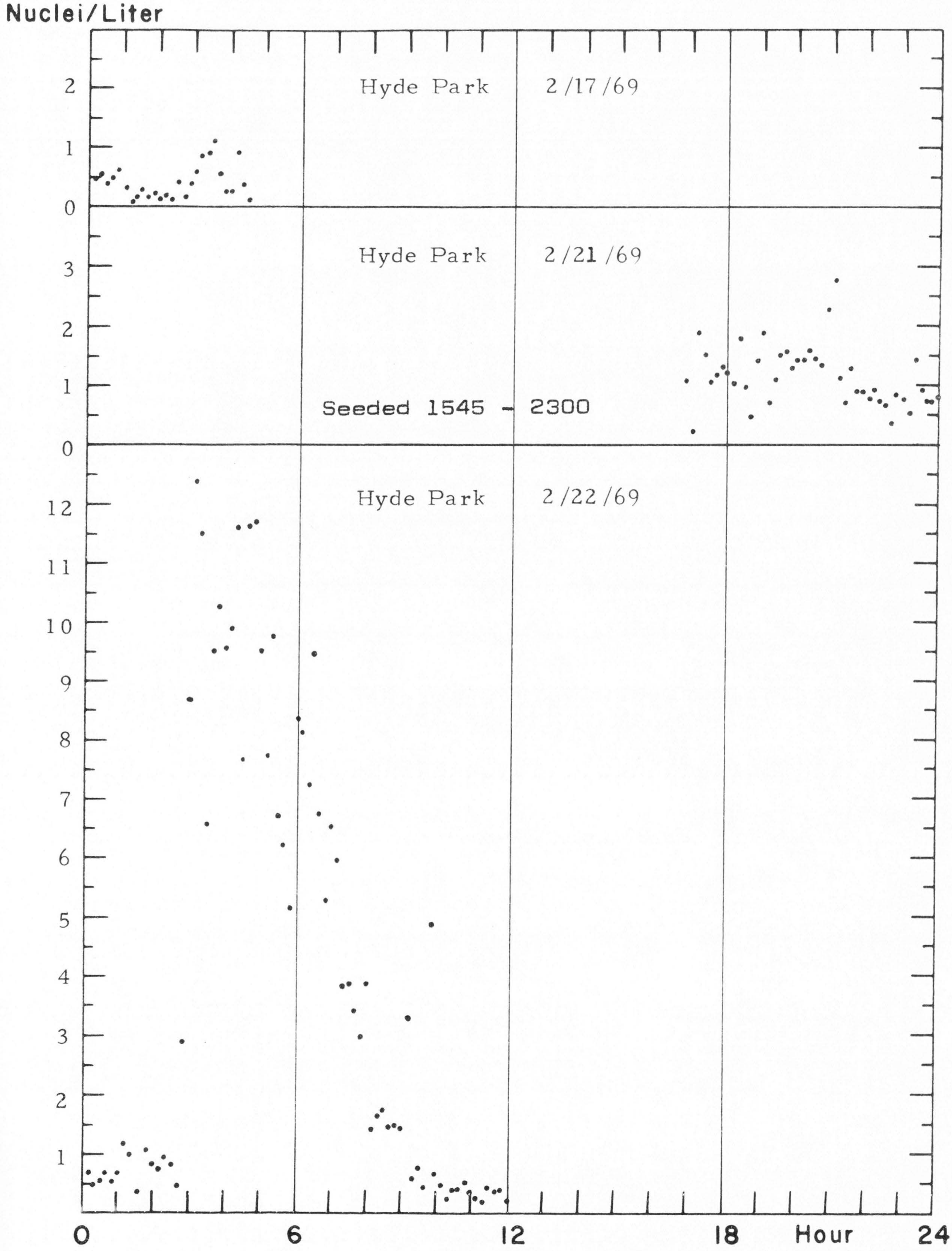
EXPERIMENTAL EVENTS:

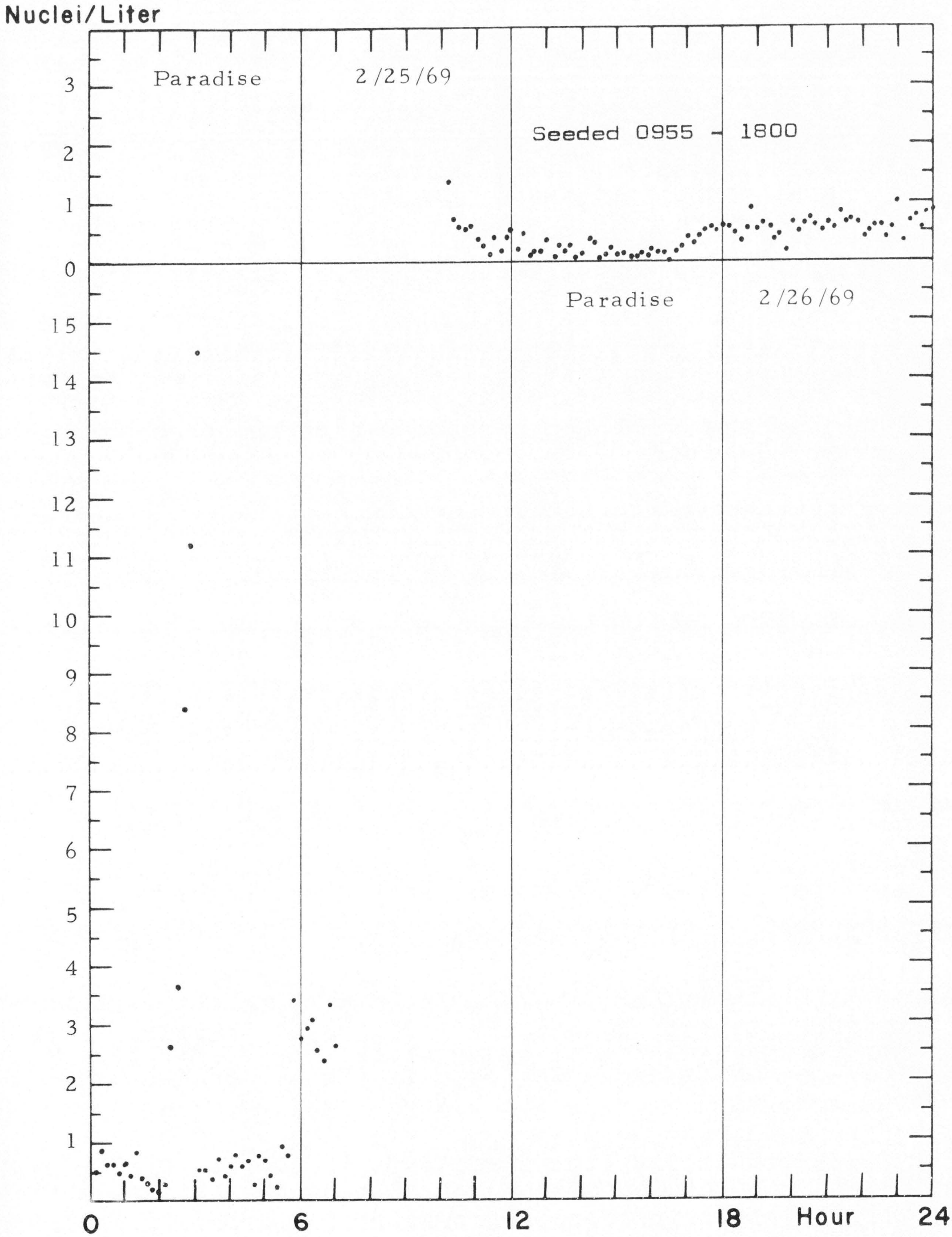
GROUND SEEDING

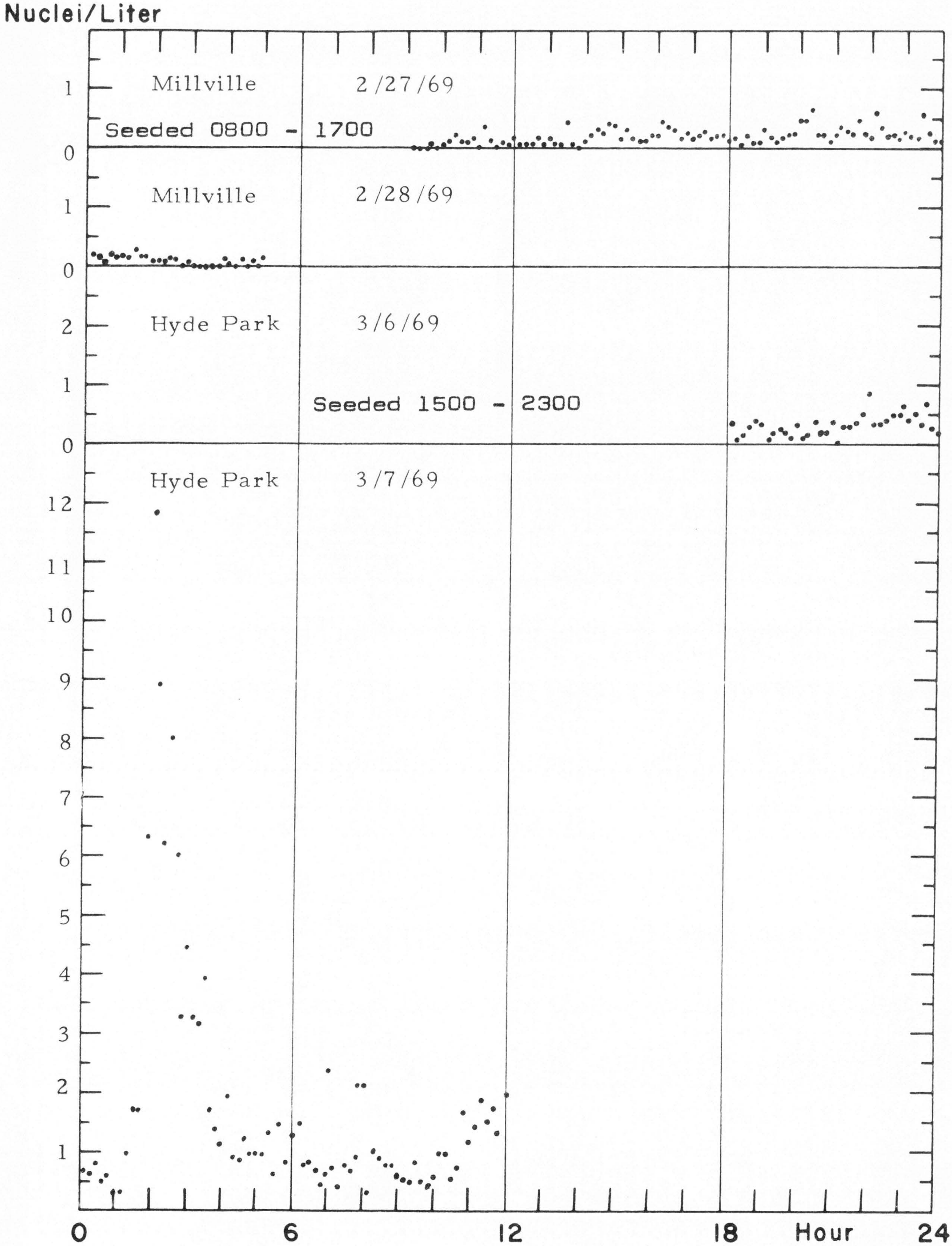


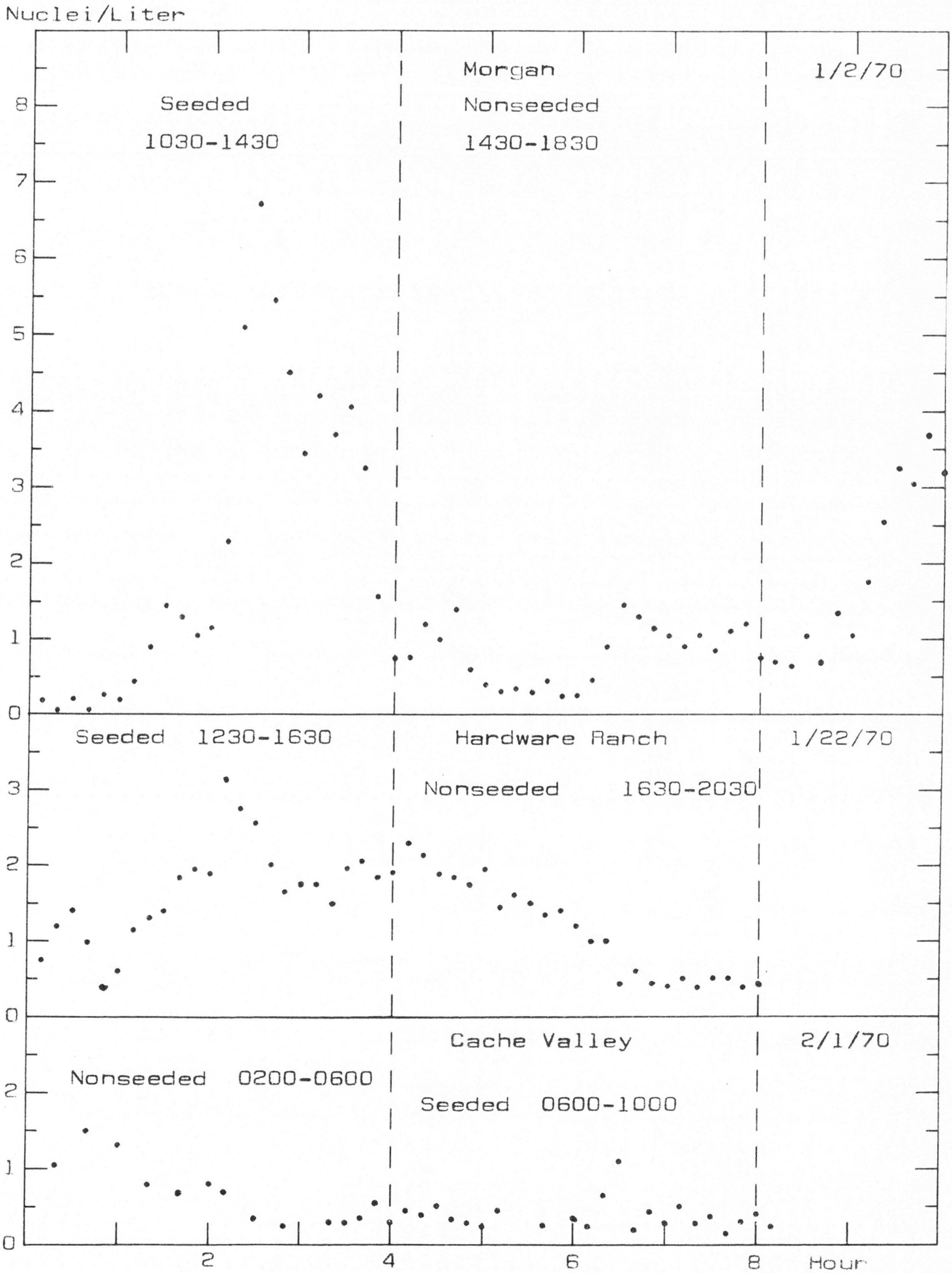
Nuclei/Liter
Hyde Park
1/21/69
Seeded 1610 - 2010
Hyde Park
1/22/69
UWRL
2/4/69
Seeded 1630 - 2400
UWRL
2/5/69
Seeded 0000 - 1130
Avon
2/13/69
Seeded 0820 - 1700
Avon
2/14/69
Hyde Park
2/15/69
Seeded 1630 - 2400
0
6
12
18
Hour
24

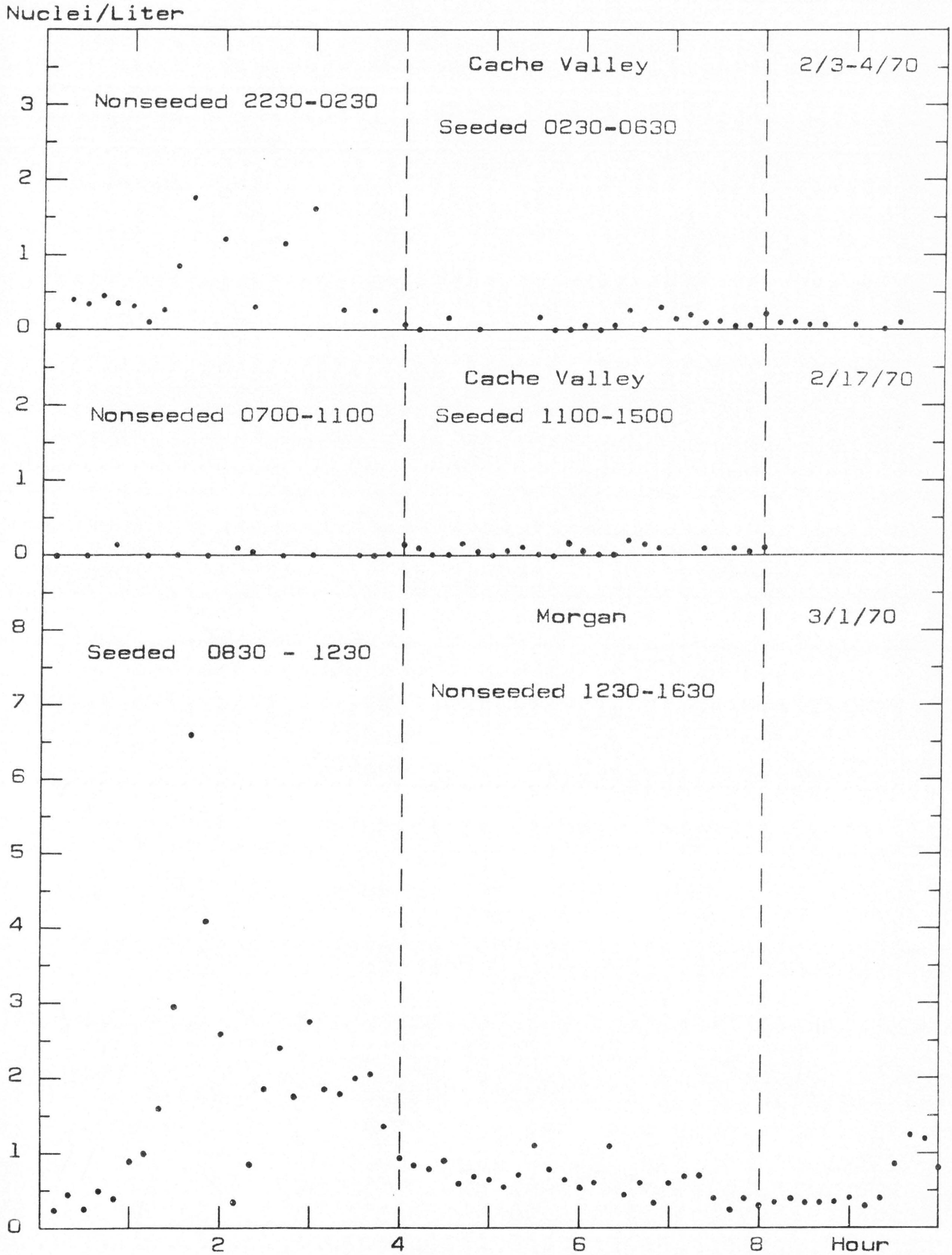

Nuclei/Liter
Hyde Park 2/16/69
Seeded 1130 - 1530
60.0
34.0
41.0
30.5
25.5
22.5
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
0
6
12
18
Hour
24

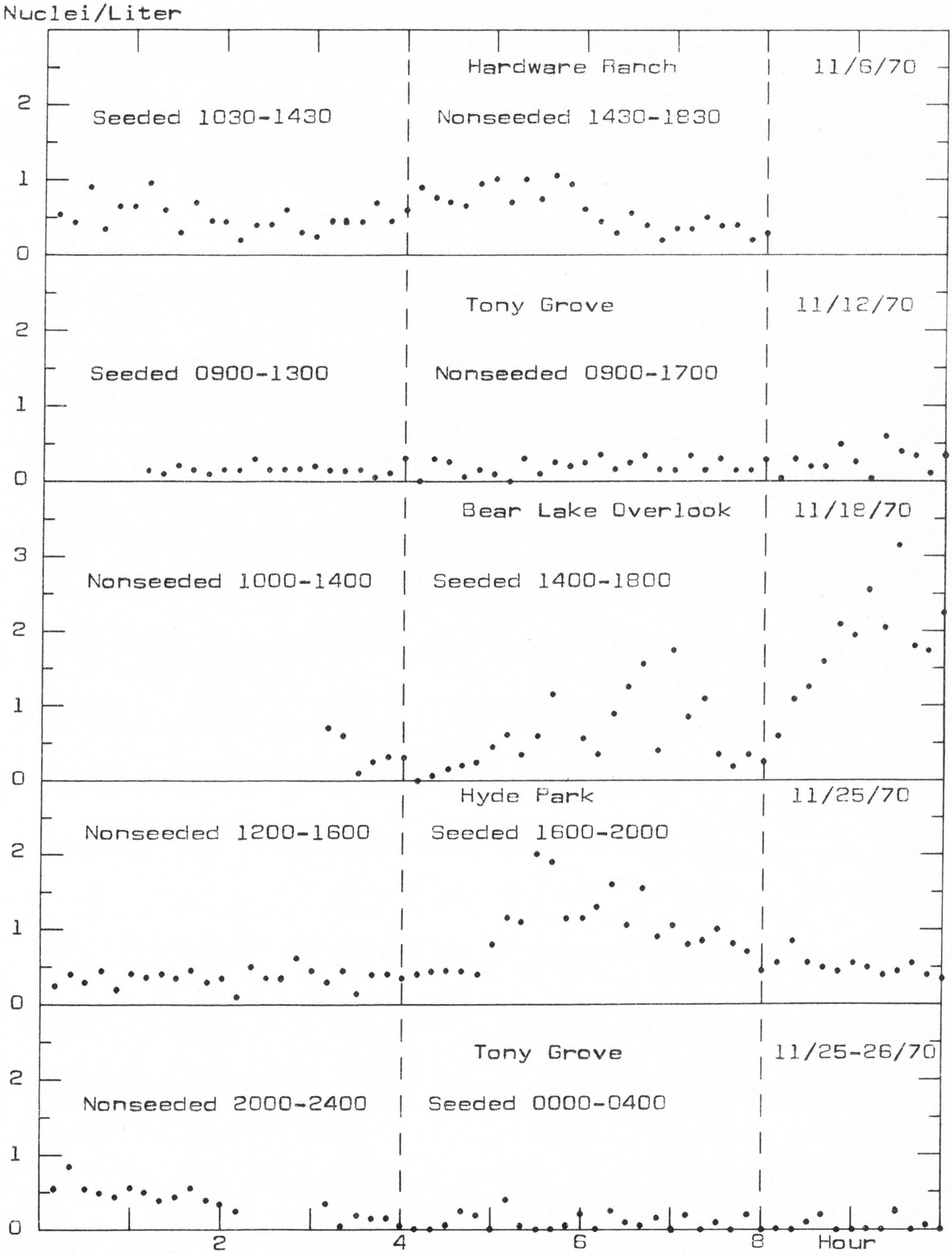

Nuclei/Liter
Hyde Park 2/17/69
Hyde Park 2/21/69
Seeded 1545 - 2300
Hyde Park 2/22/69
0
6
12
18
Hour
24
2
1
0
3
2
1
0
12
11
10
9
8
7
6
5
4
3
2
1


Nuclei/Liter
Paradise
2/25/69
Seeded 0955 - 1800
Paradise
2/26/69
3
2
1
0
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
6
12
18
Hour
24

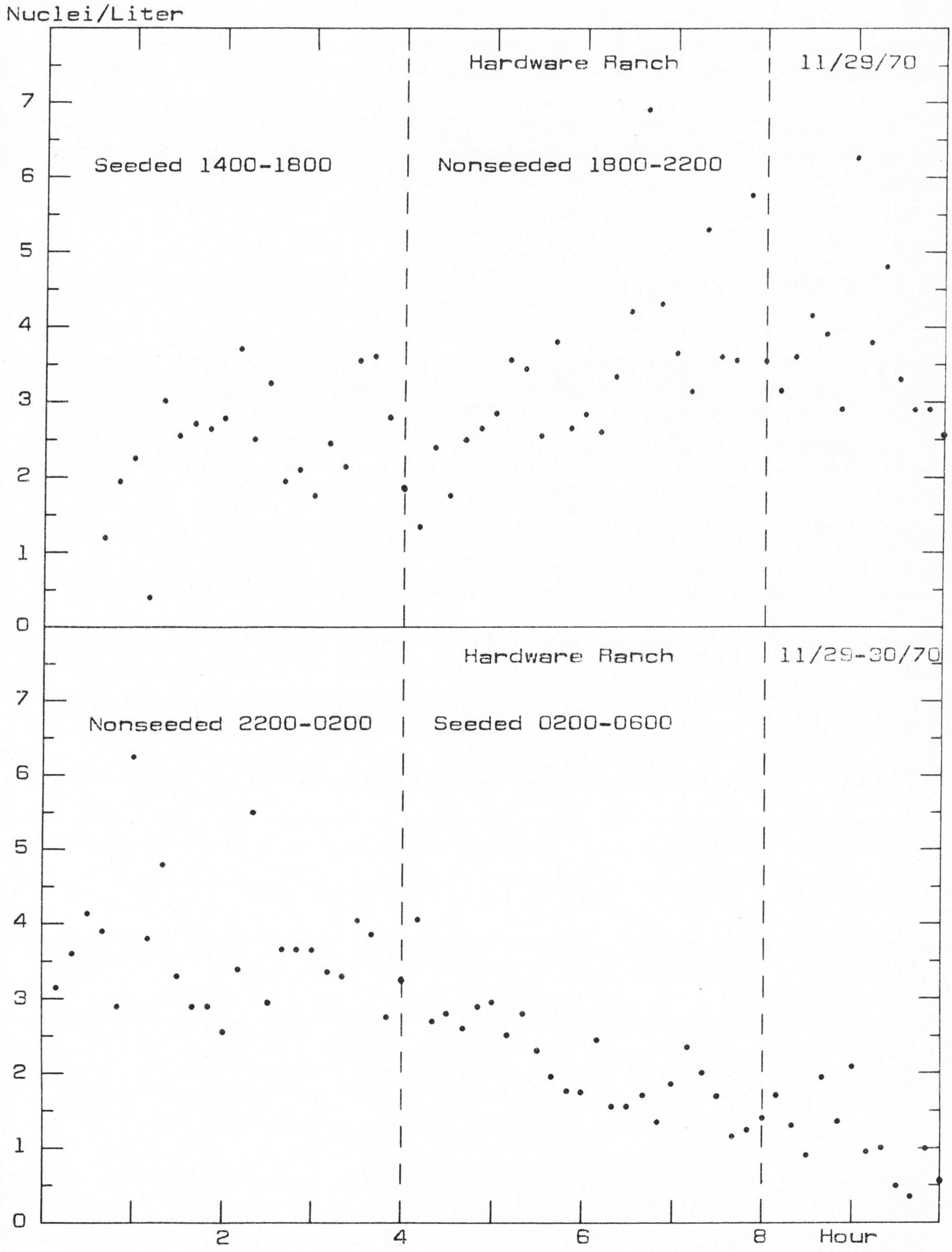

Nuclei/Liter
Millville
2/27/69
Seeded 0800 - 1700
Millville
2/28/69
Hyde Park
3/6/69
Seeded 1500 - 2300
Hyde Park
3/7/69
0
6
12
18
Hour
24
1
2
3
4
5
6
7
8
9
10
11
12

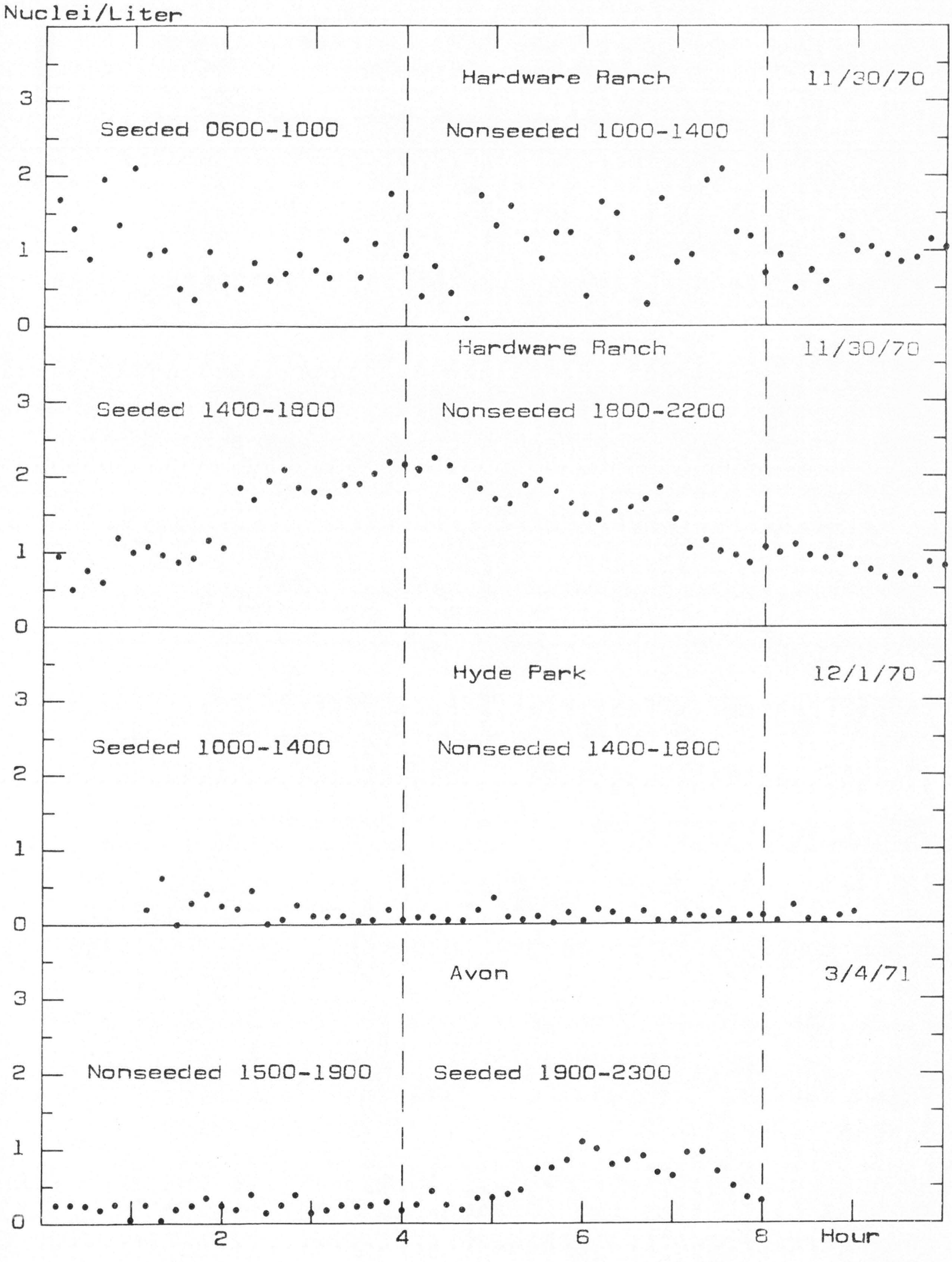

Nuclei/Liter
Morgan
1/2/70
Seeded
1030-1430
Nonseeded
1430-1830
Seeded 1230-1630
Hardware Ranch
1/22/70
Nonseeded 1630-2030
Cache Valley
2/1/70
Nonseeded 0200-0600
Seeded 0600-1000
0
1
2
3
4
5
6
7
8
2
4
6
8
Hour


Nuclei/Liter
Cache Valley
2/3-4/70
Nonseeded 2230-0230
Seeded 0230-0630
3
2
1
0
Cache Valley
2/17/70
Nonseeded 0700-1100
Seeded 1100-1500
2
1
0
Morgan
3/1/70
Seeded 0830 - 1230
Nonseeded 1230-1630
8
7
6
5
4
3
2
1
0
2
4
6
8
Hour



Nuclei/Liter
Hardware Ranch
11/6/70
Seeded 1030-1430
Nonseeded 1430-1830
Tony Grove
11/12/70
Seeded 0900-1300
Nonseeded 0900-1700
Bear Lake Overlook
11/18/70
Nonseeded 1000-1400
Seeded 1400-1800
Hyde Park
11/25/70
Nonseeded 1200-1600
Seeded 1600-2000
Tony Grove
11/25-26/70
Nonseeded 2000-2400
Seeded 0000-0400
0
1
2
3
2
4
6
8
Hour


Nuclei/Liter
Hardware Ranch
11/29/70
Seeded 1400-1800
Nonseeded 1800-2200
Hardware Ranch
11/29-30/70
Nonseeded 2200-0200
Seeded 0200-0600
0
1
2
3
4
5
6
7
2
4
6
8
Hour

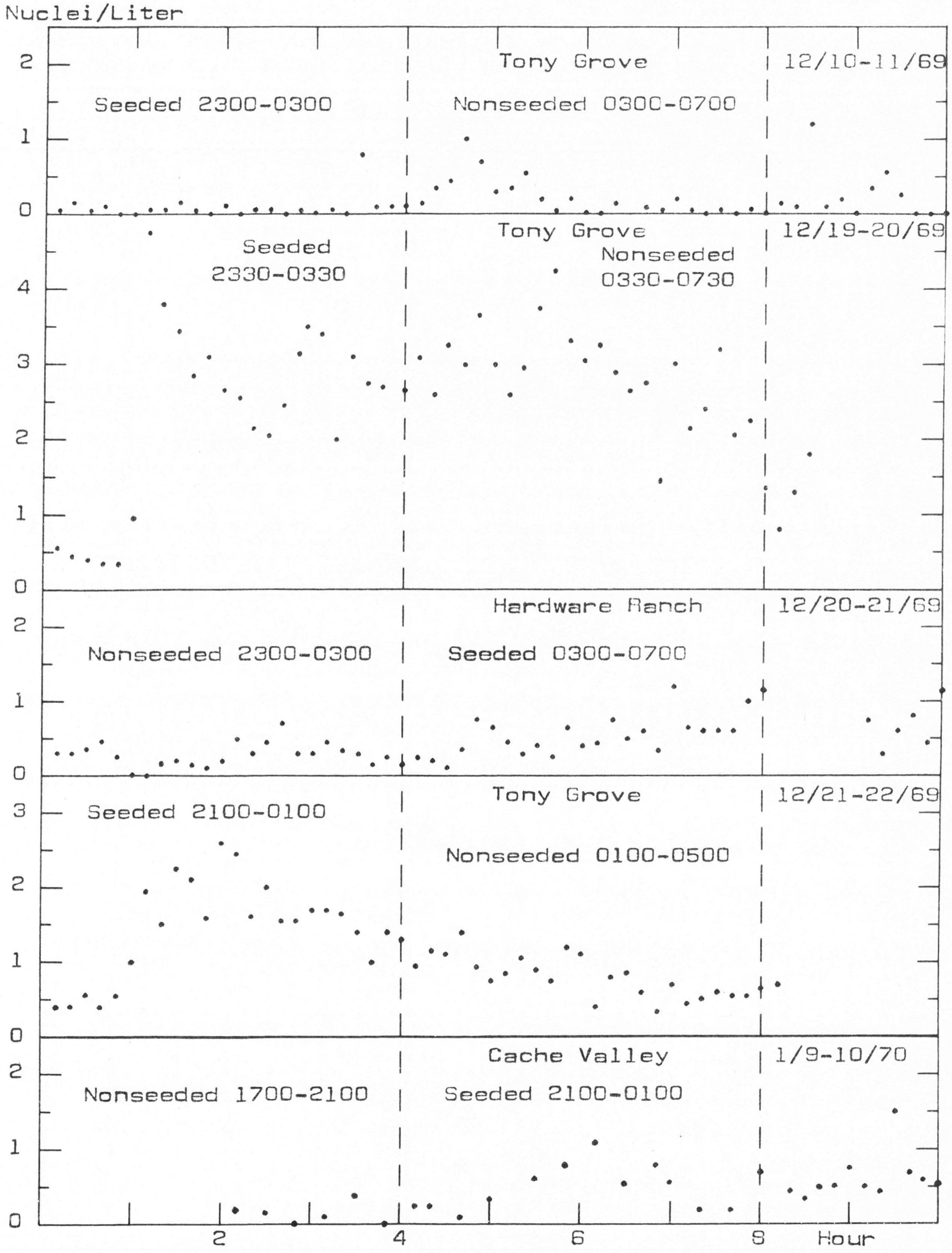


Nuclei/Liter
Hardware Ranch
11/30/70
Seeded 0600-1000
Nonseeded 1000-1400
Hardware Ranch
11/30/70
Seeded 1400-1800
Nonseeded 1800-2200
Hyde Park
12/1/70
Seeded 1000-1400
Nonseeded 1400-1800
Avon
3/4/71
Nonseeded 1500-1900
Seeded 1900-2300
0
1
2
3
2
4
6
8
Hour

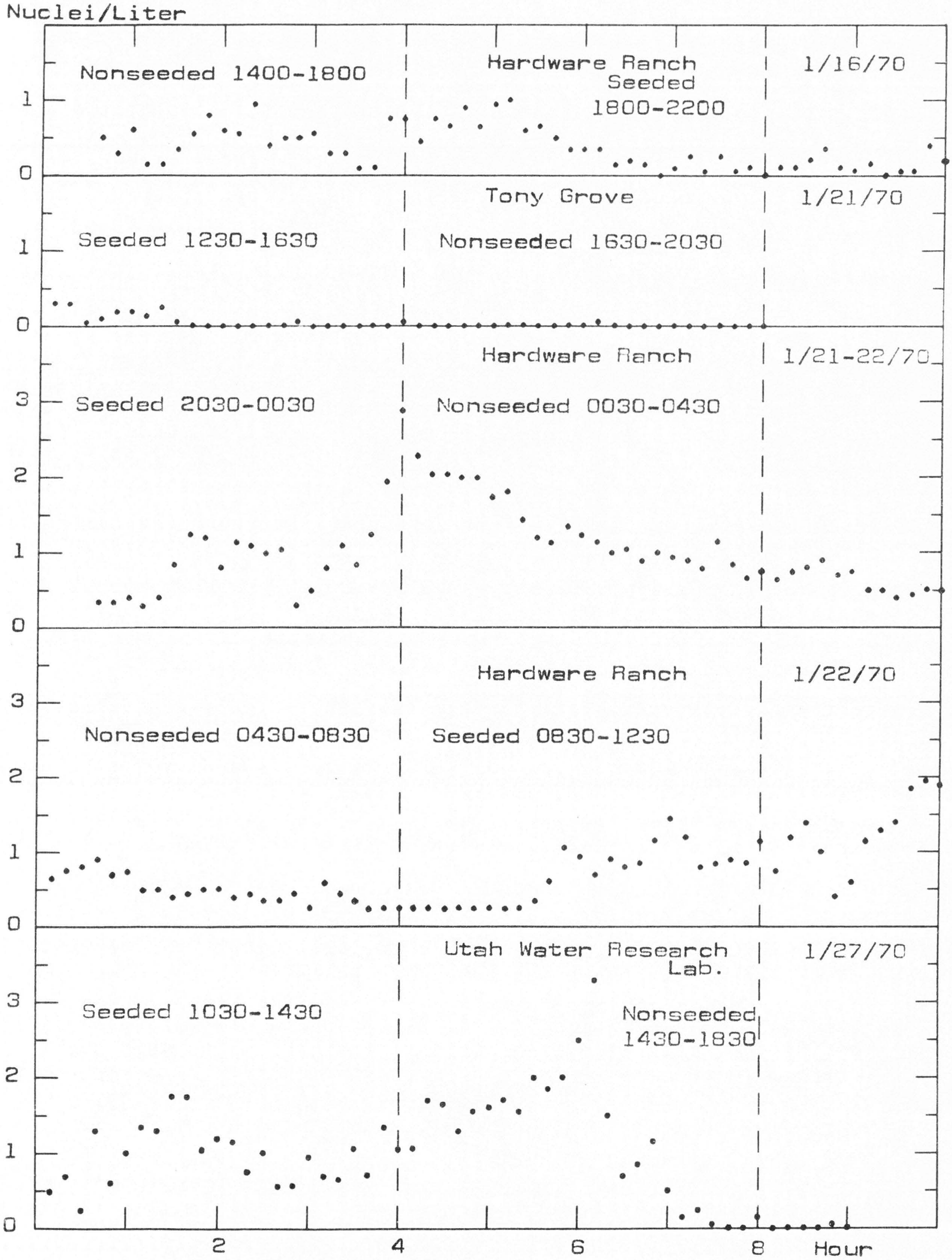
APPENDIX III

EXPERIMENTAL EVENTS:

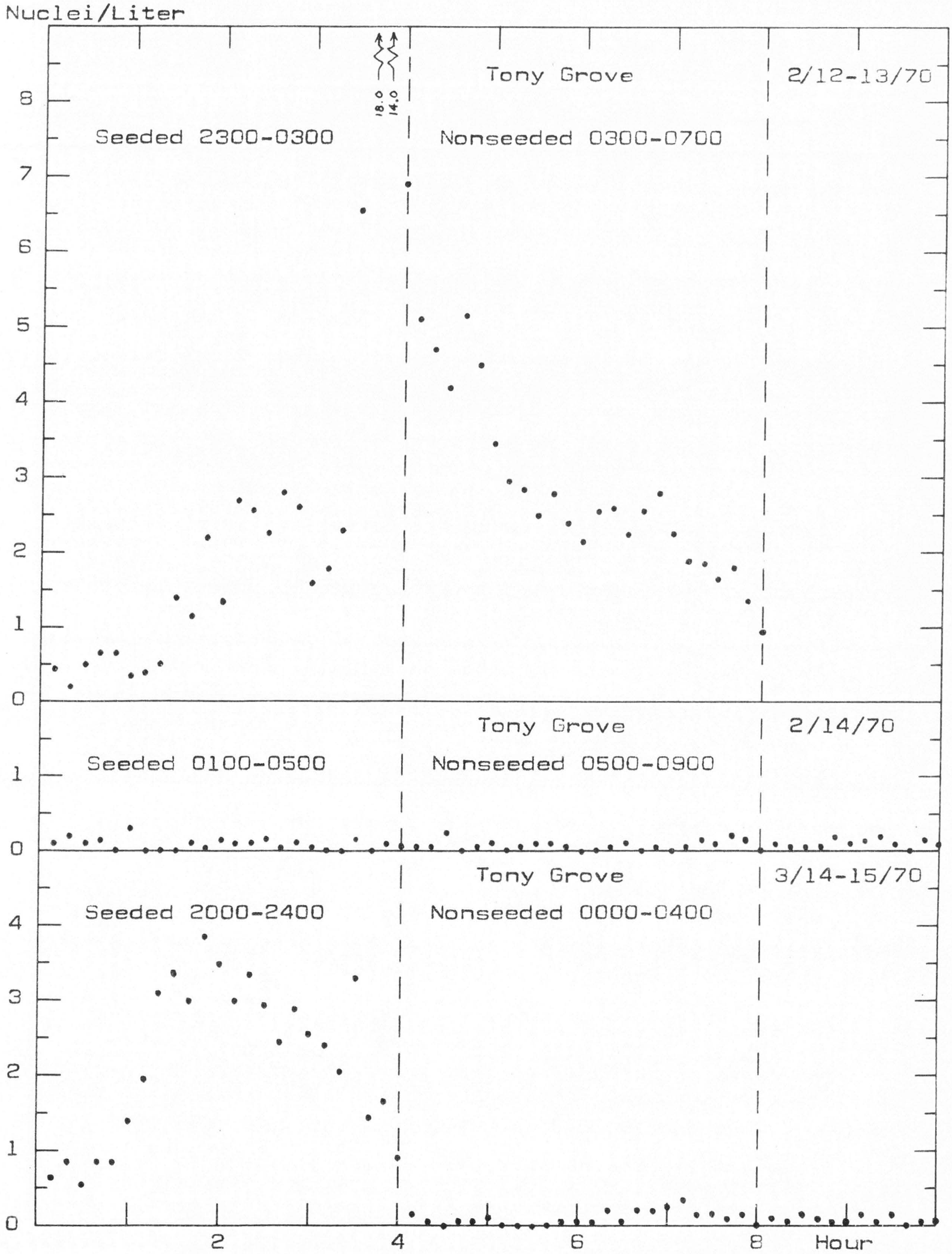
AIRBORNE SEEDING

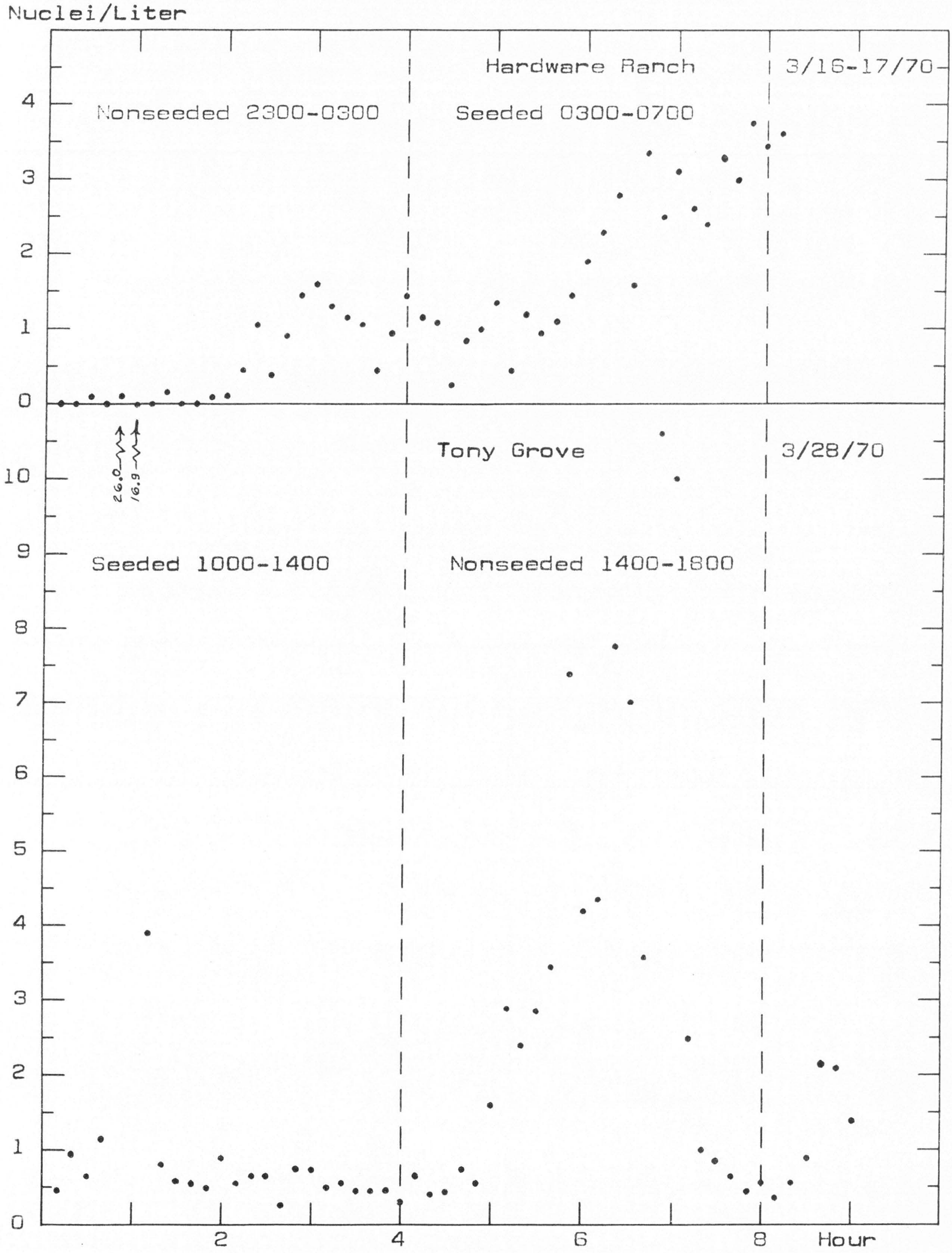


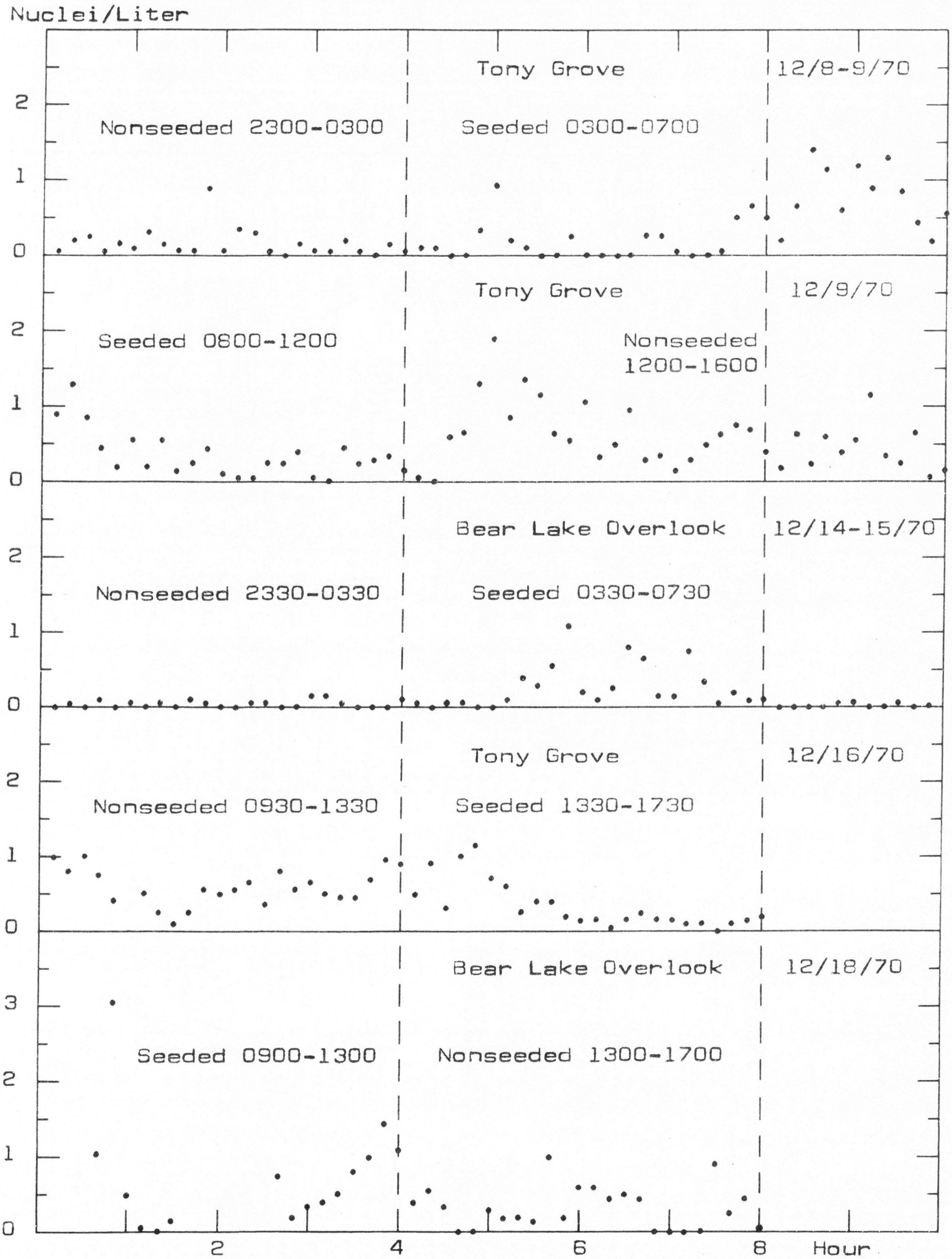
Nuclei/Liter
Tony Grove
12/10-11/69
Seeded 2300-0300
Nonseeded 0300-0700
Tony Grove
12/19-20/69
Seeded
2330-0330
Nonseeded
0330-0730
Hardware Ranch
12/20-21/69
Nonseeded 2300-0300
Seeded 0300-0700
Tony Grove
12/21-22/69
Seeded 2100-0100
Nonseeded 0100-0500
Cache Valley
1/9-10/70
Nonseeded 1700-2100
Seeded 2100-0100
2
4
6
8
Hour



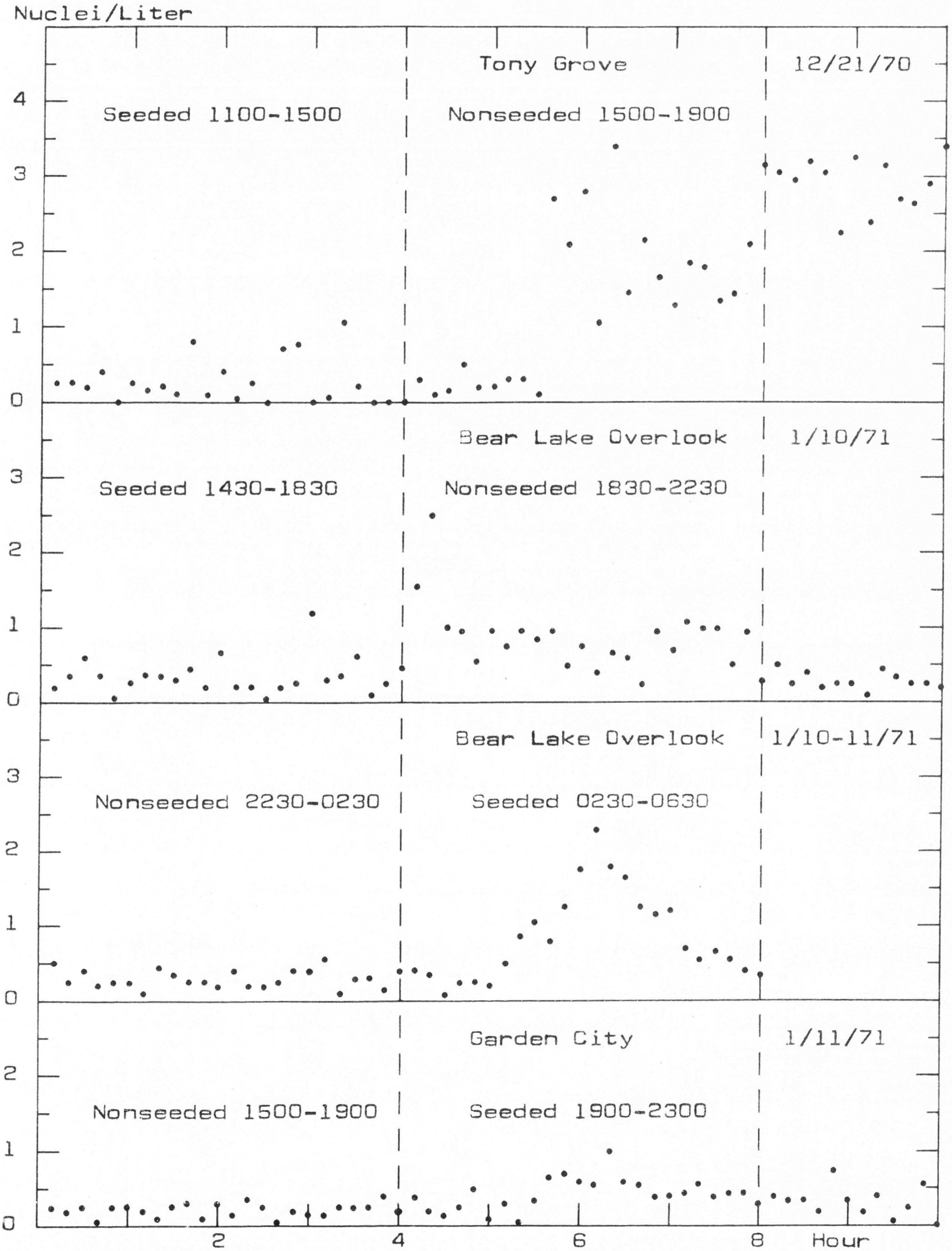
Nuclei/Liter
Nonseeded 1400-1800
Hardware Ranch
Seeded
1800-2200
1/16/70
Tony Grove
Seeded 1230-1630
Nonseeded 1630-2030
1/21/70
Hardware Ranch
1/21-22/70
Seeded 2030-0030
Nonseeded 0030-0430
Hardware Ranch
1/22/70
Nonseeded 0430-0830
Seeded 0830-1230
Utah Water Research
Lab.
1/27/70
Seeded 1030-1430
Nonseeded
1430-1830
0
1
2
3
2
4
6
8
Hour


Nuclei/Liter
Tony Grove
2/12-13/70
Seeded 2300-0300
Nonseeded 0300-0700
18.0
14.0
Tony Grove
2/14/70
Seeded 0100-0500
Nonseeded 0500-0900
Tony Grove
3/14-15/70
Seeded 2000-2400
Nonseeded 0000-0400
0
1
2
3
4
5
6
7
8
2
4
6
8
Hour

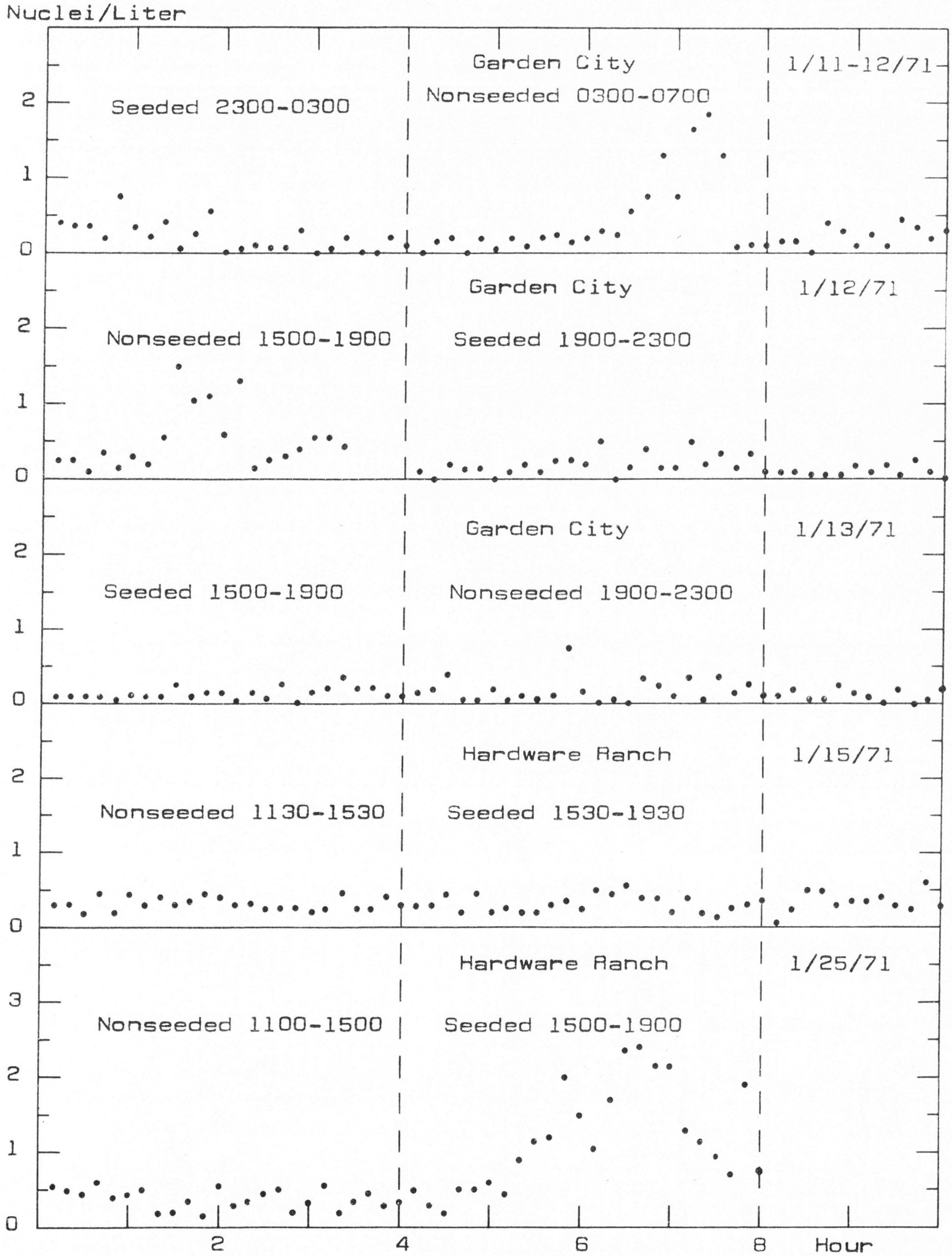

Nuclei/Liter
Hardware Ranch
3/16-17/70
Nonseeded 2300-0300
Seeded 0300-0700
26.0
16.9
Tony Grove
3/28/70
Seeded 1000-1400
Nonseeded 1400-1800
Hour

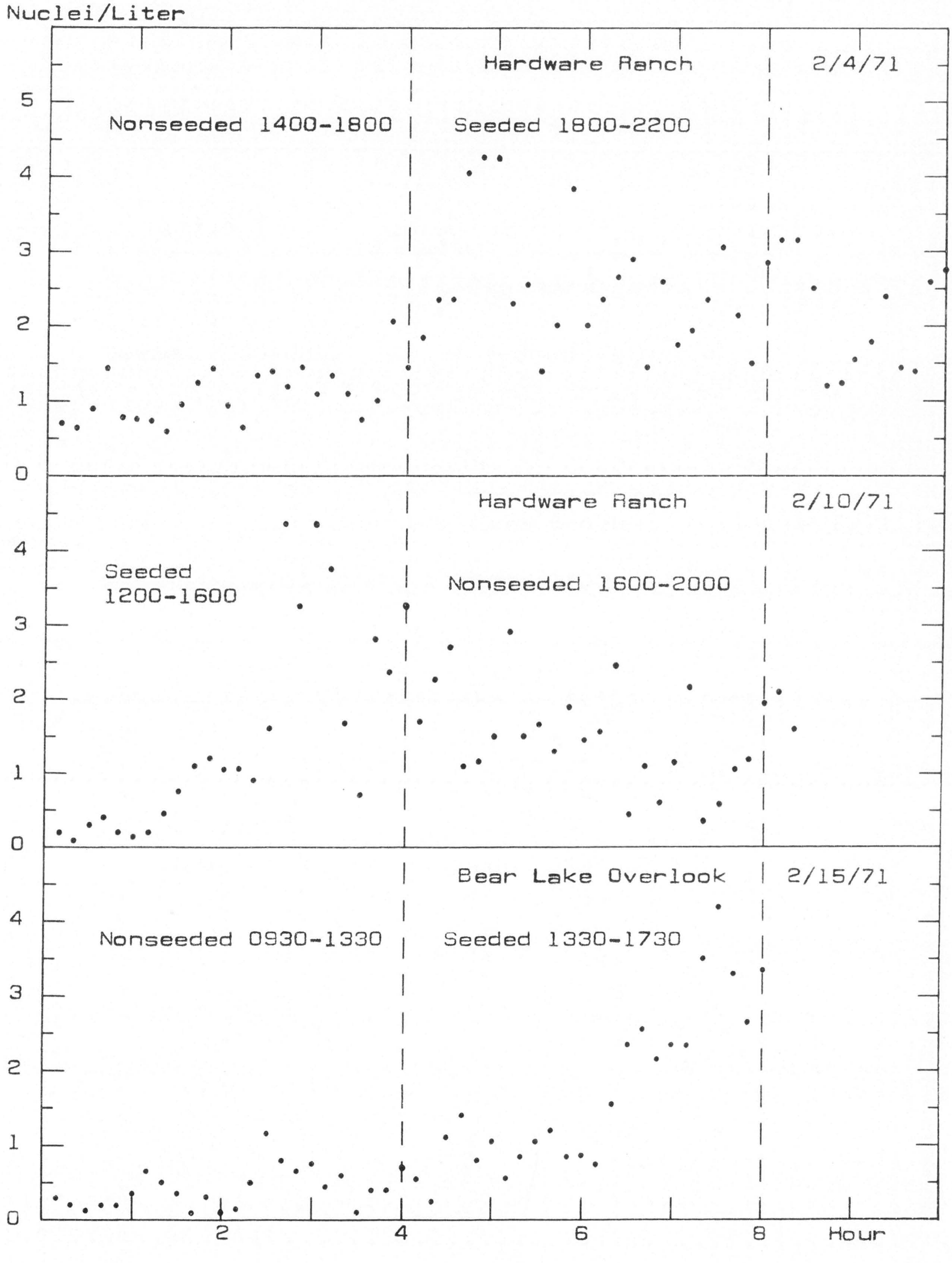


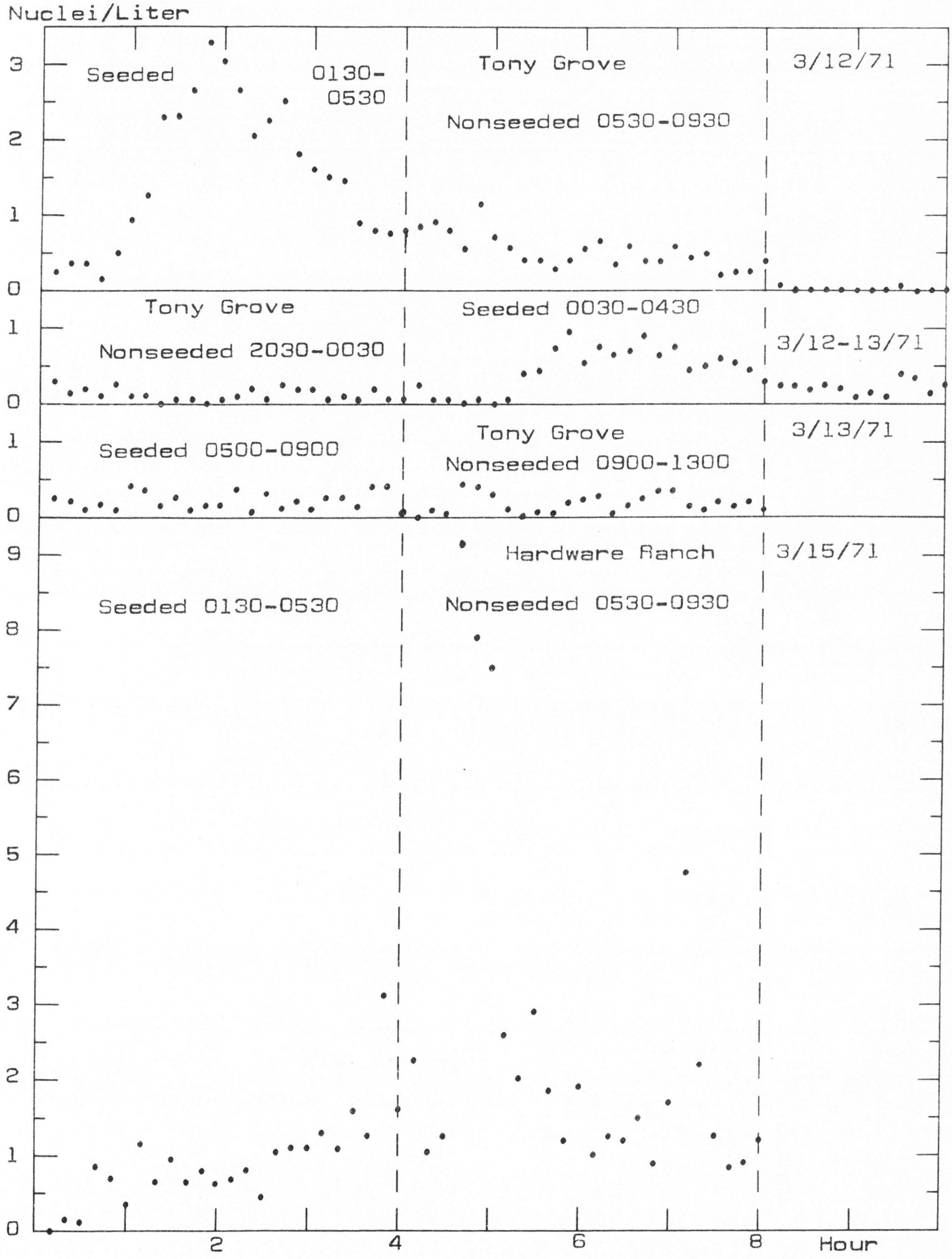
Nuclei/Liter
Tony Grove
12/8-9/70
Nonseeded 2300-0300
Seeded 0300-0700
Tony Grove
12/9/70
Seeded 0800-1200
Nonseeded
1200-1600
Bear Lake Overlook
12/14-15/70
Nonseeded 2330-0330
Seeded 0330-0730
Tony Grove
12/16/70
Nonseeded 0930-1330
Seeded 1330-1730
Bear Lake Overlook
12/18/70
Seeded 0900-1300
Nonseeded 1300-1700
0
1
2
3
2
4
6
8
Hour



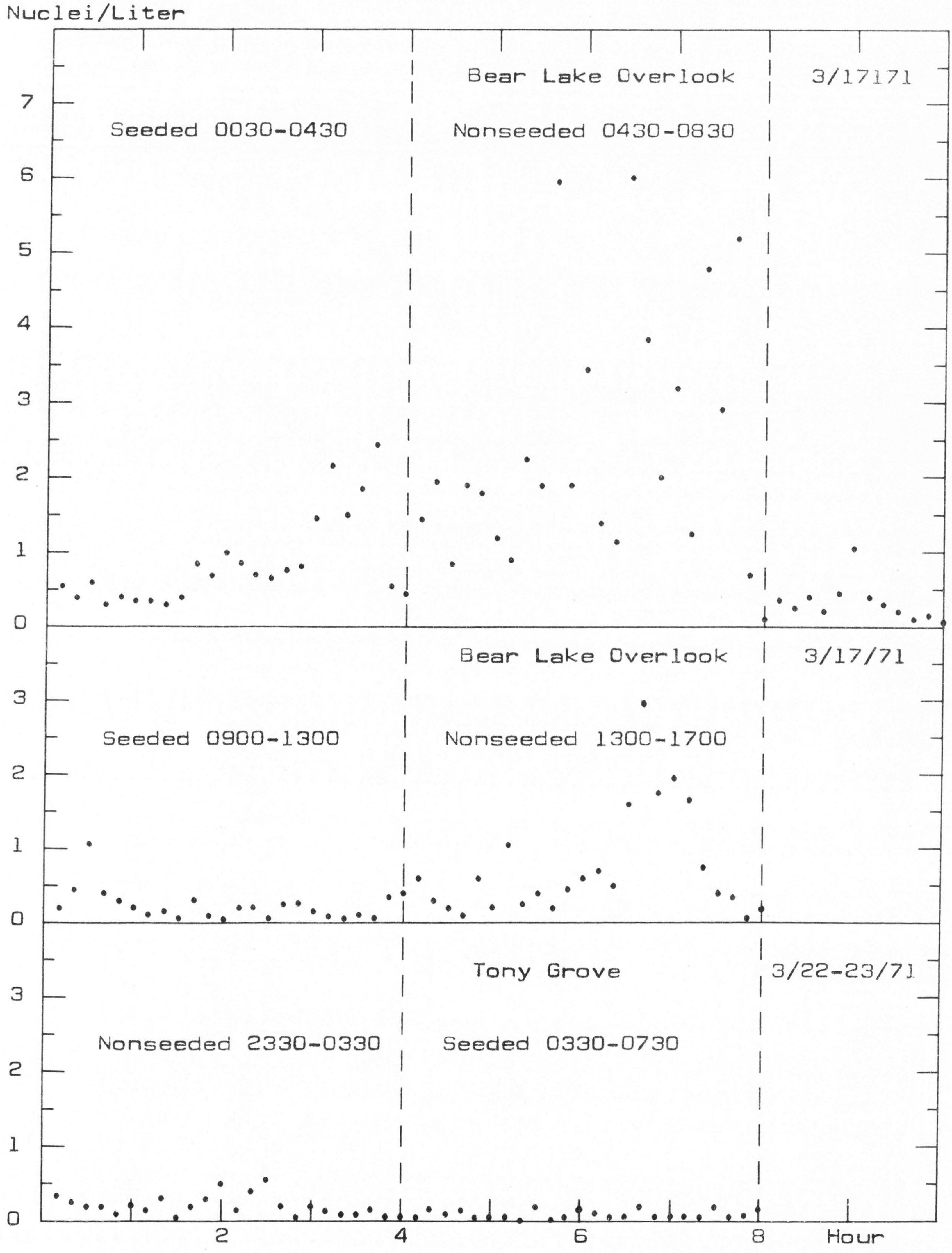
Nuclei/Liter
Tony Grove
12/21/70
Seeded 1100-1500
Nonseeded 1500-1900
Bear Lake Overlook
1/10/71
Seeded 1430-1830
Nonseeded 1830-2230
Bear Lake Overlook
1/10-11/71
Nonseeded 2230-0230
Seeded 0230-0630
Garden City
1/11/71
Nonseeded 1500-1900
Seeded 1900-2300
0
1
2
3
4
2
4
6
8
Hour


Nuclei/Liter
Garden City
1/11-12/71
Seeded 2300-0300
Nonseeded 0300-0700
Garden City
1/12/71
Nonseeded 1500-1900
Seeded 1900-2300
Garden City
1/13/71
Seeded 1500-1900
Nonseeded 1900-2300
Hardware Ranch
1/15/71
Nonseeded 1130-1530
Seeded 1530-1930
Hardware Ranch
1/25/71
Nonseeded 1100-1500
Seeded 1500-1900
0
1
2
3
2
4
6
8
Hour

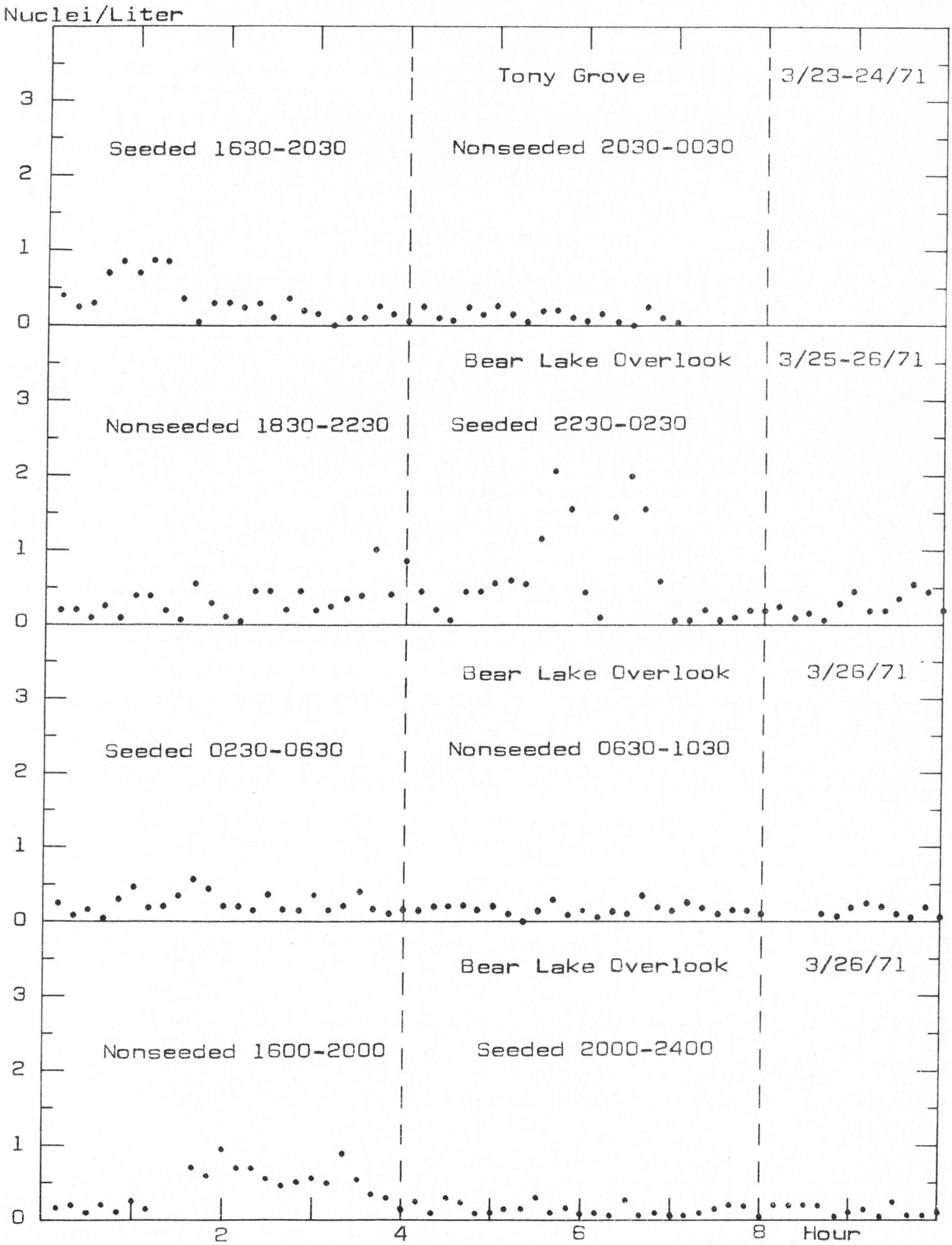

Nuclei/Liter
Hardware Ranch
2/4/71
Nonseeded 1400-1800
Seeded 1800-2200
Hardware Ranch
2/10/71
Seeded
1200-1600
Nonseeded 1600-2000
Bear Lake Overlook
2/15/71
Nonseeded 0930-1330
Seeded 1330-1730
0
1
2
3
4
5
2
4
6
8
Hour



Nuclei/Liter
Seeded 0130-0530
Tony Grove
Nonseeded 0530-0930
3/12/71
Tony Grove
Nonseeded 2030-0030
Seeded 0030-0430
3/12-13/71
Seeded 0500-0900
Tony Grove
Nonseeded 0900-1300
3/13/71
Hardware Ranch
Seeded 0130-0530
Nonseeded 0530-0930
3/15/71
Hour



Nuclei/Liter
Bear Lake Overlook
3/17171
Seeded 0030-0430
Nonseeded 0430-0830
Bear Lake Overlook
3/17/71
Seeded 0900-1300
Nonseeded 1300-1700
Tony Grove
3/22-23/71
Nonseeded 2330-0330
Seeded 0330-0730
0
1
2
3
4
5
6
7
2
4
6
8
Hour



Nuclei/Liter
Tony Grove
3/23-24/71
Seeded 1630-2030
Nonseeded 2030-0030
Bear Lake Overlook
3/25-26/71
Nonseeded 1830-2230
Seeded 2230-0230
Bear Lake Overlook
3/26/71
Seeded 0230-0630
Nonseeded 0630-1030
Bear Lake Overlook
3/26/71
Nonseeded 1600-2000
Seeded 2000-2400
0
1
2
3
2
4
6
8
Hour

VITA

William Frederick Slusser

Candidate for the Degree of

Master of Science

Thesis: Ice Nuclei Inventory: Wasatch Weather Modification Experimental Area

Major Field: Soil Science and Biometeorology

Biographical Information:

Personal Data: Born at Canton, Ohio, March 31, 1941, son of Fred W. and Fern B. Slusser; married Dolores C. Lukas June 10, 1967.

Education: Attended elementary school in North Industry, Ohio; graduated Valedictorian from Birmingham High School, Van Nuys, California, 1959; received the Associate of Arts degree from Los Angeles Pierce College in 1962; received the Bachelor of Arts degree with a double major in Biology and Geography in 1964 and completed the requirements for the Master of Arts degree, specializing in Geography and Ecology at San Fernando Valley State College, Northridge, California in 1968.

Professional Experience: 1968 to 1972, research assistant, Utah Water Research Laboratory working on the Wasatch Weather Modification Project; 1966-68, supervisor, data analyst and technical writer, San Fernando Valley State College Foundation; 1966 summer trainee in computer programming, National Center for Atmospheric Research (NCAR), Boulder, Colorado; 1964-1966, weather observer and research assistant, San Fernando Valley State College, Geography Department.